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ENGINEERING EXPERIMENT STATION

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TESTS OF REINFORCED CONCRETE BEAMS: RESISTANCE TO WEB STRESSES. SERIES OF 1907 AND 1908.

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AND APPLIED MECHANICS.

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I. INTRODUCTION.

1. *Scope of Bulletin.*—Tests of reinforced concrete beams made in various laboratories have provided a considerable fund of information bearing on the part played by the tensile resistance of the longitudinal reinforcement and the compressive resistance of the concrete. The data on resistance to web stresses are less definite and less complete. In beams having a depth relatively large in comparison with their length, the resistance to web stresses becomes very important, and diagonal tension and bond stresses may control the strength of the beam. It was with a view of obtaining further information on web stresses and on the part taken by concrete, bent reinforcement, and stirrups in resisting web stresses that these series of tests were undertaken.

The tests were carried on during the years 1906-7 and 1907-8. Tests were made on (1) beams without web reinforcement, (2) beams with reinforcing bars bent up in various ways along the outer thirds of their length, and (3) beams with vertical U-shaped stirrups. Four span lengths were used. Various amounts of longitudinal reinforcement from 1 % to 2.2 % were used. Tests were made with concrete at different ages with a view of determining the effect of early removal of forms. Six mixtures of concrete were used, ranging from very lean to very rich. Compression tests of cubes and cross-bending tests of small concrete beams, called here control beams, were made with a view of determining whether a relation between the strength of the reinforced concrete beams and the control pieces might be found which would be useful as a control test in building construction. 117 beams were made in 1907 and 71 beams in 1908. 106 of these were without web reinforcement, 27 had the reinforcing bars bent up in one form or another, and 55 had stirrups for the web reinforcement. It was found impossible to carry out the tests exactly as planned, and the data of the tests do not furnish a basis for as definite conclusions as had been hoped. However, the tests throw light on the phenomena of web resistance and the results have a bearing on the principles of design. Reference may also be made to the values of web resistance reported in Bulletins No. 4 and No. 14.

2. *Acknowledgment.*—The investigations were made in the Laboratory of Applied Mechanics of the University of Illinois as a part of the work of the University of Illinois Engineering Experiment Station. Much of the work of making the tests of the beams was done as thesis work by senior students in civil engineering. The following list gives the names of the students engaged in this work. They are entitled to credit for the care, skill, and interest which they showed in the work, as well as for the suggestive way in which they discussed the results.

Tests of Reinforced Concrete Beams.

Series of 1907.

Chester A. Foreman, Carl James, Leon B. Kinsey. Resistance to web stresses.

Frank Howard Reynolds. Effect of storage and consistency.

Francis Cyrus Bagby, Augustus Bacon Casey. Modulus of elasticity for various mixtures.

Edwin Walker Buxton. Effect of bending and anchoring reinforcing bars.

William Hadden Richardson. Flexural strength of concrete.

Series of 1908.

Raymond Clark Pierce, Hiram James Powers, Robert Milton Van Petten. Resistance to web stresses.

Arthur Linn Bear, Samuel Charles Campbell. Modulus of elasticity for various ages and mixtures.

Otto Arthur Dicke. Tests of flexural strength of concrete.

The immediate supervision of the work of making the beams and of the work of conducting the tests was given by D. A. Abrams, Associate in the Engineering Experiment Station. Acknowledgment is also made to H. E. Murdock, Instructor in Theoretical and Applied Mechanics, for assistance in the preparation of this bulletin.

3. *Classification of Stresses.*—A brief statement of the methods of analysis and of the formulas used in the calculations and discussions given in this bulletin, so far as is necessary to make clear the matter presented, is given in the following pages. This presentation necessarily must be incomplete, and some of the statements made are given tentatively and are to be taken with limitations. In the discussion freedom from end restraint of any kind is always assumed, and in the tests care was exercised to secure the same condition.

In the analysis of beam action, two classes of stresses are considered; (1) the horizontal or longitudinal component stresses (tension and compression) which are used in the calculation of the resisting moment of the section, and (2) diagonal, vertical, and horizontal stresses, like shear and diagonal tension and diagonal compression, which constitute what are frequently termed web stresses. The first named stresses and the resisting moment resulting therefrom in many cases measure the ability of the beam to carry the required load. With reinforced concrete beams, however, the second type of stresses under conditions which are not unusual, may be the limiting element in the strength of the beam, and the resistance to such stresses therefore constitutes an important feature of a well designed beam. These web stresses may include bond stress (resistance to slip of reinforcing bar in the concrete), shearing stresses in various directions, and tensile stresses and compressive stresses in directions other than that parallel to the axis of the beam. The calculation of the amount and distribution of the web stresses is complicated, and for use in design it will be convenient to use certain assumptions and approximations. The discussion will be made under three heads: (1) Beams without Web Reinforcement. (2) Beams with Bars Bent Up, and (3) Beams with Stirrups.

4. *Notation.*—The following notation will be used. Reference may also be made to Fig. 1.

b = breadth of rectangular beam.

d = distance from the compression face to the center of the metal reinforcement.

A = area of cross section of longitudinal reinforcement.

$p = \frac{A}{bd}$ = ratio of area of metal reinforcement to area of concrete above center of reinforcement.

o = circumference or periphery of one reinforcing bar.

m = number of reinforcing bars.

E_s = modulus of elasticity of steel.

E_c = initial modulus of elasticity of concrete in compression.

$n = \frac{E_s}{E_c}$ = ratio of two moduli.

f = tensile stress per unit of area in metal reinforcement.

c = compressive stress per unit of area in most remote fiber of concrete.

d' = distance from the center of the reinforcement to center of gravity of compressive stresses.

j = ratio d' to d. $d' = jd$.

ΣX = summation of horizontal compressive stresses.

M = resisting moment at the given section.

s = horizontal tensile stress per unit of area in the concrete.

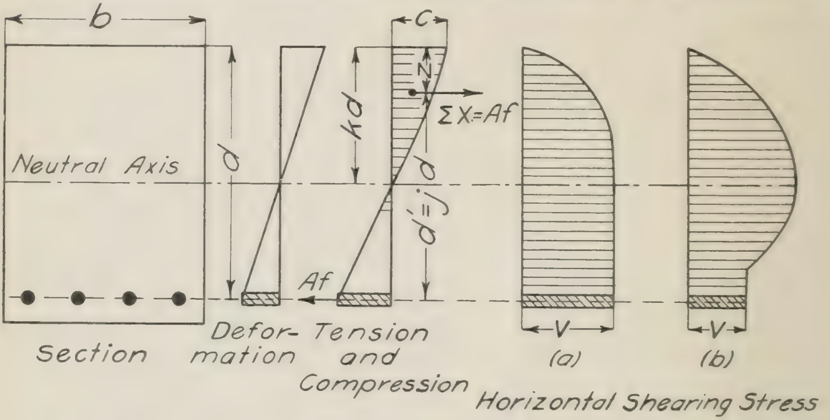

FIG. 1. DISTRIBUTION OF STRESSES OVER CROSS-SECTION OF BEAM.

t = diagonal tensile stress per unit of area in the concrete.

u = bond stress per unit of area on the surface of the reinforcing bars.

v = vertical shearing stress and horizontal shearing stress per unit of area in the concrete.

5. *Resisting Moment.*—In the calculation of the resisting moment of reinforced concrete beams, it is the usual practice to neglect the tension in the concrete. At sections where the bending moment is a maximum this is allowable. With this assumption the expression for the resisting moment (see Fig. 1) is

$$M = Afd' = Afjd \qquad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

jd is here used as the equal of d'. Its exact value is to be determined by the methods given on pages 16 and 17 of Bulletin No. 4. The value of j for the beams discussed in this bulletin varies from 0.80 to 0.88.

For sections nearer the point of zero bending moment (as for example, in simple beams near the supports), tension exists in the concrete from the neutral axis downward for some distance and even to the bottom of the beam. It is evident that for such portions of the beam the presence of this tension should be taken into consideration in the discussion of web resistance. It is also evident that the formula for resisting moment given above, if applied to such portions of the beam, would involve considerable error.

6. *Beams without Web Reinforcement: Bond Stresses.*—In order to have beam action there must be a proper web connection between the tension and the compression portions of the beam. When there is no metallic web reinforcement, the concrete acts alone as this web. It is clear, of course, that the amount of stress in the reinforcing bars and also in the compression area of the concrete varies from cross-section to cross-section along the length of the beam. The increment of tension and that of compression gained between consecutive sections must be connected by means of this web; that is, the increment in the tensile stress in the reinforcing bars must be transferred to or connected with the increment of the compressive stress in the concrete.

In transmitting the increment of stress from the reinforcing rods to the surrounding concrete there is developed a tendency of the rods to slip in the concrete, and the amount of resistance to slip thus developed is called bond and will be measured in terms of the area of surface in contact with the concrete. It will be seen that the total bond developed on the surface of the bars in one inch of length is equal to the total change in the amount of tension in the bars for the same inch of length. Bond may be compared to the action of the rivets joining flange to web in a riveted steel girder, except that in a reinforced concrete beam the contact is continuous.

For beams in which the reinforcement is horizontal or straight throughout, the formula for bond may be derived as follows if the tensile strength of the concrete in resisting longitudinal stresses is neglected. At any vertical section of the beam the value of the resisting moment is given by equation (13) ($M = Afd'$), where f is the unit stress in the steel at the section considered and d' is the distance from the center of the steel to the center of compression in the concrete. Differentiating this equation, $\frac{dM}{dx} = A\frac{df}{dx}d'$. By the principles of mechanics of beams, $\frac{dM}{dx} = V$, where

V is the total vertical shear at the given section (reaction at support minus loads between the support and the section considered). Substituting and transposing,

$$\frac{Adf}{dx} = \frac{V}{d'} \quad \text{.............................(16)}$$

Now the derivative $\frac{Adf}{dx}$ expresses the rate of change of the total tensile stress in the reinforcing bars at the section under consideration; it is given in terms of a unit of length of beam (pounds per inch of length) and measures what is transmitted to the concrete by the bond. Using m as the number of bars, o as the efficient circumference or periphery of one bar, the total surface of bars for one inch of length of beam is mo and the bond stress developed is mou, where u represents the bond developed per unit of area of surface of bar. Equating this to the value of the derivative in equation (16) and solving,

$$u = \frac{V}{mod'} \quad \text{.............................(17)}$$

Attention should be called to the fact that equation (17) is derived for beams having the reinforcing bars straight throughout their length, that tension in the concrete is neglected, and that it must be modified in case any or all of the bars are bent up. If the longitudinal tension in the concrete is considered, as it may need to be near the ends of the beam it will be found that the bond developed will be less than given by the formula if the value of f is derived directly from the bending moment. In one portion of the beam there will be tension in concrete from the neutral axis down to the bottom of the beam; close to this, tension will exist for but a short distance below the neutral axis. For the portion of the beam between these two conditions the bond developed will be even more than that given by the formula.

7. *Vertical and Horizontal Shearing Stresses in Beams without Web Reinforcement.*—It is shown in the mechanics of beams that there exists throughout a beam vertical and horizontal shearing stresses which vary in intensity, and that at any point in a beam the vertical shearing unit-stress is equal to the horizontal shearing unit-stress there developed. As noted in the discussion of bond, the total tension in the reinforcing bars varies along the length of the beam, as does also the total compressive stress. The

horizontal shearing stress is seen to be necessary in order that the increments or increase of the total tensile stresses in the reinforcing bars (transmitted to the surrounding concrete by the bond stresses), may be transmitted to the corresponding increments of compression in the compression area of the concrete. The concrete thus forms the stiffening web of the beam.

The amount of this horizontal tensile stress so transmitted from the reinforcing bars per unit of length of beam is by equation (17) $mou=\frac{V}{d'}$. Consider this distributed over a horizontal section just above the plane of the bars for a unit of length of beam, and call the horizontal shearing unit-stress v. The shearing resistance per unit of length of beam thus developed is then bv, and equating this to mou,

$$v=\frac{V}{bd'} \quad \text{..............................} (18)$$

This equation gives the horizontal shearing unit-stress, and therefore also the vertical shearing unit-stress, at a point just above the level of the reinforcing bars. As no tension is here considered as acting in the concrete, there will be no change in the intensity of the horizontal and vertical shearing stresses between this level and the neutral axis. Above the neutral axis the intensity of the shearing stresses will decrease by the law of change of horizontal shearing stresses for homogeneous rectangular beams modified to suit any variation from the straight-line stress-deformation relation. The distribution of the intensity of the horizontal shearing stress over a vertical section is represented in Fig. 1 (a).

As d' may range from $0.80\,d$ to $0.88\,d$ for the conditions of the beams here considered, the shearing stress by equation (18) is from 25% to 13% more than the average shearing stress or than that found by considering the stress to be uniformly distributed over a vertical section extending down to the center of the reinforcing rods.

The presence of longitudinal tension in the concrete modifies the distribution of the vertical shear, increasing the shearing stress at the neutral axis and decreasing it at the level of the reinforcement. If the total tension taken by the concrete be estimated, and also the position of the centroid, the proportion of the bending moment taken by the steel and by the tensile stresses of the concrete may be determined. If now the total vertical shear V be separated into two parts which are proportional to these moments, respectively, the part V' taken by the steel may be used in equation (18), and the part V'' taken by the tension of the concrete may be used in a similar way by considering the distance to the centroid of the tension in the concrete. Fig. 1 (b) illustrates the distribution of the vertical shear in this case.

Although the presence of tension in the concrete modifies the amount and distribution of the shearing stresses, equation (18) will be used in the discussion of the tests of beams having the bars straight throughout, since it is simpler to neglect the tension and since the results are satisfactory for the purpose of comparison.

8. *Diagonal Tension in Concrete in Beams without Web Reinforcement.*—In the flexure of a beam various stresses are set up in its web. Besides the bond and the horizontal and vertical shearing stresses already discussed, tensile and compressive and shearing stresses exist in every diagonal direction. In determining the resisting moment, only the horizontal components of these are taken. When there is no metallic web reinforcement, all the diagonal stresses are taken by the concrete. By the analysis of combined shear and tension given in text books on resistance of materials, the value of the maximum diagonal tensile unit-stress is found to be

$$t = \tfrac{1}{2}s + \sqrt{\tfrac{1}{4}s^2 + v^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

where t is the diagonal tensile unit stress, s is the horizontal tensile unit-stress existing in the concrete, and v is the horizontal or vertical shearing unit-stress. The direction of this maximum diagonal tension makes an angle with the horizontal equal to one-half of the angle whose cotangent is $\frac{1}{2}\frac{s}{v}$

If there is no tension in the concrete this reduces to

$$t = v \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

and the maximum diagonal tension makes an angle of 45° with the horizontal and is equal in intensity to the vertical shearing stress at that point.

It is seen that the value of the diagonal tensile stress depends upon the tensile stress in a horizontal direction at the given point as well as upon the amount of the horizontal and vertical shearing stresses there developed. If $s = 0$, $t = v$, and the diagonal tension has this value in a direction 45° from the horizontal. If $s = v$, $t = 1.62\,v$ and the direction of the maximum stress makes an angle of 31° 43′ with the horizontal. If $s = 2\,v$, $t = 2.4\,v$ and the direction of the maximum stress is 27° 30′. It may be said that in the ordinary reinforced concrete beam the value of t probably varies from one to two times v, the vertical shearing unit-stress.

It is evident that the value of the diagonal tension is generally indeterminate. No working formulas are available. For this reason it is the practice, now becoming nearly universal, in beams without web reinforcement to calculate the value of the vertical shearing unit-stress v, and to use this as the measure or means of comparison of the diagonal tensile stress developed in the beam; with the understanding, of course, that the actual diagonal tension is considerably greater than the vertical shearing stress. It will be found that the value of v developed in beams will vary with the amount of reinforcement, with the relative length of the beam, and with other factors which affect the stiffness of the beam.

9. *Diagonal Tension and Bond Failures in Beams without Web Reinforcement.*—It is evident that the tensile strength of the concrete may limit the strength of a reinforced concrete beam and that under certain conditions diagonal tension may be the cause of failure. These failures will occur in the outer parts of the length of the beam. The difference between the condition of tension in the concrete at this portion of the beam and that at the points of maximum bending moment should be noted. In the latter place the concrete will have failed in tension from the bottom of the beam to some point not far below the neutral axis, and under this condition tension in the concrete has little effect upon the resisting moment. This section is likely to be at a point in the beam where the shearing stresses are low. Failure by diagonal tension comes at a point in the beam where the longitudinal tensile stresses are less and the vertical shearing stresses are greater. The tensile strength of the concrete in beams without web reinforcement forms the principal source of resistance to diagonal tension.

Failure by diagonal tension (commonly called shear failure) generally starts from a tension crack which has formed at the bottom of the beam and extended to the level of the reinforcement or to a point somewhat above. This crack then branches in a diagonal direction, running in a direction away from the support. If the diagonal crack starts from a point some distance above the level of the reinforcement, as it may in a deep beam, it will also run diagonally downward in the prolongation of the general diagonal line. Failure by diagonal tension is generally sudden, as is the case when concrete is tested in tension and as is found in tests of unreinforced concrete beams. A variation from this is found when part of the shear is carried forward by the stiffness of the rods, and the failure is slower and progressive. Fig. 2 gives typical representations of a failure by diagonal tension in beams having all the bars straight. In the second case the reinforcing bars are finally split off from the concrete above.

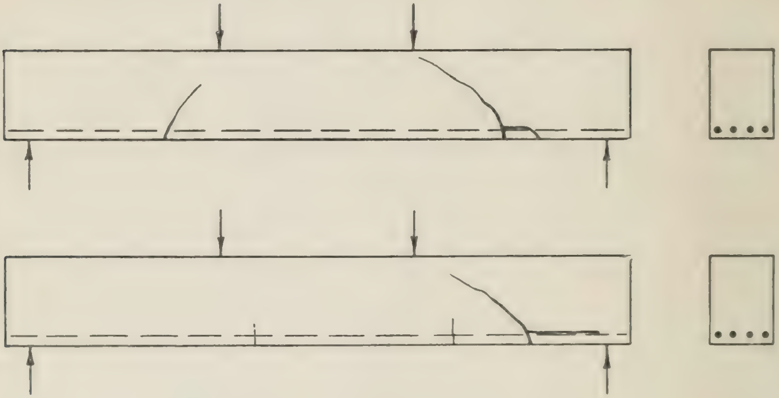

FIG. 2. POSITION OF CRACKS IN DIAGONAL TENSION FAILURES.

10. *Phenomena of Beam Action with Bars Bent Up.*—When bars are bent up in the outer portion of the beam length, the distribution and the amount of the shearing stresses and bond stresses are materially different from the foregoing. The analysis of the stresses becomes more complex; a determination of their actual value is impracticable. However, a study of the phenomena of failure and of the conditions which exist and of their variation from the conditions ordinarily assumed in the analysis of beams

with all bars horizontal, will serve a useful purpose. Comparisons may be made by means of the formulas for bond, shear, and diagonal tension already referred to.

The case where all bars are bent up at the same point will first be taken up. Assume the method of loading used in the tests, that of placing the loads at the one-third points of the span length. In Fig. 3 (a), G is the support and F the load point where one half of the load is applied. Take any section AB at some point between the support and the load point. If we assume that the ordinary conditions of beam action exist, it will be seen that the concrete will break in tension from some point B at the bottom of the beam up to C, and with an increase of the load applied and with the increased tension and stretch in the reinforcing bar this tension crack will extend upward. With the method of loading assumed, neglecting the influence of the weight of the beam, the bending moment will increase uniformly from the support to the load point, being zero at G and a maximum at the section through F. For a beam having the reinforcement straight throughout, the common assumption of beam action would show the stress in the reinforcement to be decreasing uniformly from the load point to the support, changing from a maximum at the section through F to a zero stress at G.

With the bars bent up a different distribution of the stresses exists. We may obtain an idea of the stress at an intermediate point C, if we neglect tension in the concrete, by considering d as the distance from A to C, substituting in equation (13), p. 6, and multiplying the resulting value by $\sec \alpha$, where α is the angle which the reinforcing bar makes with the horizontal at the given point C. It is apparent that the stress in the reinforcement at C must be considerably greater than when the reinforcing bars are straight throughout. It is even conceivable, if the ordinary assumptions held, that the stress in the bars might be nearly constant to the end of the bar, as would be the case in a parabolic truss. This can not be the case in a reinforced concrete beam, however, for the tensile strength of the concrete at the bottom of the beam operates to take the greater part of the tension which goes to make up the bending moment for sections toward the end of the beam; and besides, the variation from beam action near the end of the beam (due to the distribution of the upward pressure from the support in an oblique direction and to the existence of arch action) changes the stress distribution in sections near the end of the beam. This much is brought out, however, that if the tensile stress in the steel remained uniform to the end of the bar, the bond stress required at the end of the bar would be enormous.

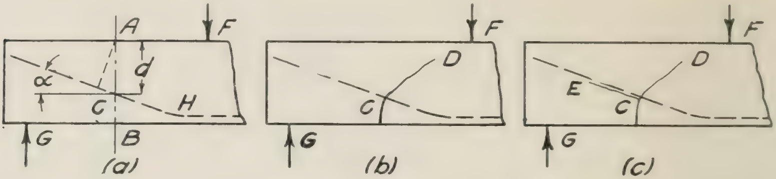

FIG. 3. DIAGONAL TENSION FAILURE IN BEAMS WITH ALL BARS BENT UP.

The presence of tensile strength in the concrete makes the above condition an impossible one; high bond stresses must also exist at certain points. Consider that at the section through C the concrete has failed in tension below the bar and that at some section nearer the support the tensile strength of the concrete is effective down to the bottom of the beam. It is evident that at the latter section the stress in the bar must be relatively small (since it is here so close to the neutral axis of the beam). The change in stress in the bar between the two sections must then be considerable and hence the bond developed on the surface of the bar will be very great, much greater than is given by the formulas as ordinarily applied. Of course, it is probable that under the actual conditions of stress the cross-section of the beam will become distorted and a plane section before bending will not remain a plane section after bending; this adds to the indeterminateness of the phenomena.

It is evident that any modification of the distribution of the tensile stress throughout the length of the reinforcing bar and of the bond between the steel and concrete at different cross-sections must be accompanied with a change in the amount and distribution of shearing stresses and diagonal tension. Where the bond stress is small, the shearing unit-stress will be low, and any condition which increases the bond stress must also increase the shearing stress and hence also the diagonal tension.

With the reinforcing bar in a diagonal direction, part of the diagonal tension will be taken by the bar. On the other hand, the formation of a vertical crack, as at C in Fig. 3 (b), gives opportunity for the starting of a diagonal crack, and the diagonal crack is likely to form from such main vertical cracks. Whether bond or diagonal tension will be the ultimate cause of failure is, then, a subject for investigation. Another condition which enters into the action of bars with reinforcement bent up in this way is the effect of the sudden change in stiffness at the point C after the vertical and diagonal crack has formed to and beyond C. It will be seen in Fig. 3 (c) that the portion of the beam to the left of C is stiffer than that at C, and with increase of bending at C a tendency to split the concrete exists. As a result the concrete may split along the reinforcing bar from C to E as shown in the figure, and this may be the manner of failure.

When part of the bars are bent up and part remain straight, the stresses are distributed in still another way. In Fig. 4 (a) consider that part of the bars (say one-half) are bent up along IK, and that the remainder run straight toward or past the support G. Consider that at the section FH both sets of bars are at the same level and that they have the same tensile stress. Away from I toward the end of the beam, the tensile stress in the upper bars will be less than that in the lower group. If we assume that a plane section before bending remains a plane section after bending the relative deformation in the two sets of bars at the section AB may be represented as at (b) in Fig. 4. Likewise, the ratio of the tensile stresses developed at C and B (shown at (c)) may be represented by $\frac{f''}{f'} = \frac{y''}{y'}$, where f'' and f' are the tensile unit-stresses in the bars at C and B, respectively, and y'' and y' are the distances shown in the diagram. It appears, then, that the stress in the rod at B must take the greater part of the bending moment and hence that the stress in the bar at B will be correspondingly greater than that in the bar at C. As the tensile stress in the bent rod has decreased a relatively large amount between the points I and C, the bond stress developed in this portion of its length must be higher than given by the ordinary equation for bond stress; and from C to K the bond stress must be correspondingly less than the calculated value. In the lower bars the stress at B may not be much less than at I, since at B it is taking the larger part of the bending moment, and hence the bond stress developed in the portion IB will be less than that found by the formula, while beyond B and toward G the decrease in stress will be rapid and the bond stress developed will be correspondingly greater. Again it may be noted that the assumption that a plane section before bending remains a plane section after bending evidently is not exactly true, and the distortion which takes place in the concrete adds to the difficulties of determining the stresses. Fig. 4 (d) may be taken as illustrative of the change in *f* in the two sets of bars between the load point and the support under the assumption that ordinary beam action prevails, and Fig. 4 (e) as representative of the stresses with the conditions of distortion prevailing.

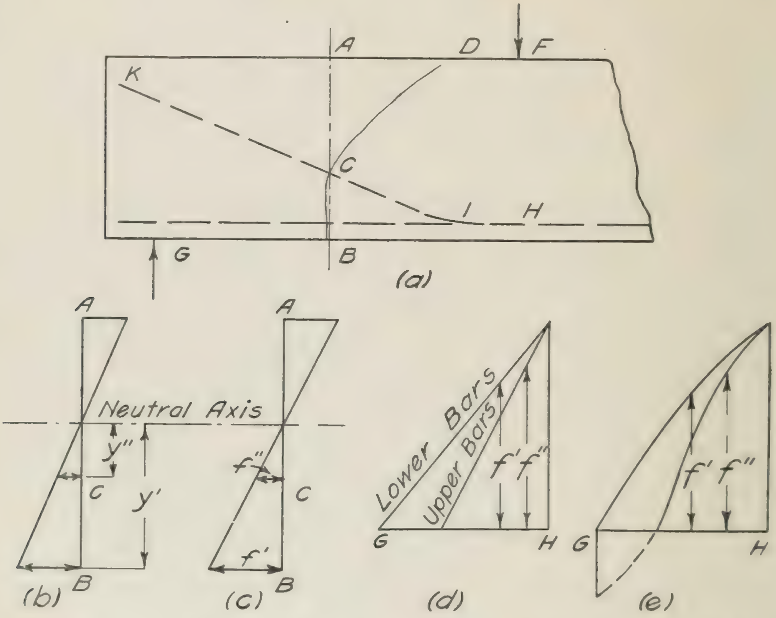

FIG. 4. DIAGONAL TENSION FAILURE IN BEAMS WITH PART OF THE BARS BENT UP.

It would seem, then, that the bending up of the bars results in greater vertical shearing stresses between I and C, and that a large part of the diagonal tension developed here will be taken by the bent reinforcement; and also that in the lower set there is less bond developed between I and B and hence that the diagonal tension throughout this portion is less than might otherwise be expected. If, now, another part of the bars were bent up at B a condition would be developed similar to that in IC. It is evident that it is not easy to determine the distribution of the diagonal stresses among the several bars, and this is especially true if they are not rigidly connected with each other.

When the main reinforcing bars run straight through the beam and diagonal reinforcement is fastened to them, or where a part of the bar is sheared and bent up, as in the Kahn bar, still another condition exists. Here the conditions of tensile stresses in the main reinforcing bars approximate those given by the ordinary beam assumptions and formulas, (modified for tension in the concrete), if the amount of metal is uniform or nearly uniform throughout the length of the beam. Most of the diagonal tension may be considered finally to be taken by the diagonal reinforcement, if its sectional area and bond resistance are sufficient and if the diagonals are properly distributed in the beam. Use V as the amount of total vertical shear at the given section which is considered to be carried through the diagonal reinforcement. The proportion which this V bears to the actual total vertical shear at the given section may not be known and possibly may have to be estimated from our knowledge of the results of tests. When the diagonals make an angle of 45° with the horizontal, the assumption that the direction of the resulting diagonal compressive stress is at an angle of 45° with the horizontal will not result in material error, particularly if the bars are bent up at intervals longitudinally equal to d' or $\frac{1}{2}d'$. For these conditions the amount of the diagonal stress finally taken by the diagonal reinforcement may be estimated to be $0.707\frac{Va}{d'}$, where a is the distance longitudinally between diagonals. This is with the provision, of course, that the diagonals are sufficiently close together and that they are securely fastened to the longitudinal bars.

Generally speaking, then, the distribution of web stresses in beams with bars bent up is more or less indeterminate. A special study of the stresses may be made for any given arrangement of bars, and recourse must be had to experimental results for each case. In this bulletin instead of attempting to calculate the actual stresses, the values given in the tables and in the discussion will be those obtained by equations (17) and (18), using for d the full depth from the top of the beam to the reinforcement as it exists at the middle of the beam; and the values so found will be termed the *nominal* shearing stress and the *nominal* bond. These nominal values will be used in comparison of results obtained with the different arrangements of bars, but it must be expressly understood that they do not represent actual stresses in the reinforcement or in the concrete.

11. *Web Reinforcement by Vertical Stirrups.*—The use of vertical stirrups to take a part or all of the vertical component of the web stresses is quite common. These stirrups are U-shaped or looped and enclose the longitudinal reinforcement and generally are not fastened to it. The following assumed conditions will be discussed in order: (1) the assumption that all the vertical component is taken by the stirrups; (2) the condition which exists before the concrete fails in diagonal tension; and (3) the conditions probably existing after the concrete has so failed.

(1). In Fig. 5 (a), the spacing of the stirrups is given as a. If a diagonal crack has formed, the condition shown in Fig. 5 (b) may exist. Following the line of reasoning used in establishing equation (18), p. 9, and assuming that the diagonal compressive stress makes an angle of 45° with the horizontal whatever may be the spacing of the stirrups, the vertical component to be taken by the stirrups per unit of length of beam is seen to be $\frac{V}{d'}$. The total stress taken by one stirrup then is

$$P = \frac{Va}{d'} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

It is assumed that enough vertical deformation has taken place to develop this stress, and that the stirrups are close enough together to make this form of reinforcement effective. It will be seen that the assumed action corresponds in some ways with the action of a truss having the line of the upper chord at the centroid of the compressive stresses.

(2). Until the concrete web has failed in diagonal tension and diagonal cracks have formed there must be little vertical deformation at the plane of the stirrups, so little that not much stress can have developed in the stirrups. Besides, at this stage the diagonal tension must be expected to be distributed along the length of the beam and not to be concentrated at the stirrups. It is evident, then, that until the concrete web fails in diagonal tension little stress is taken by the stirrups.

(3). After the diagonal cracks have formed, the lower part of the concrete web becomes ineffective in resisting diagonal tension. The stress may be considered as delivered to the stirrup at B in Fig. 5 (b) through the cantilever projection C′ B′ E. There is still integrity of structure in the upper portion of the section CD or C′D′, and since there is not freedom of movement at the compression centroid it seems reasonable to consider that not the full effect is transmitted through the cantilever portion C′B′E to B. The experiments seem to confirm this view. It will be convenient in the general discussion to consider that part of the vertical shear *V* is carried down through the cantilever C′B′E to B, and part passes through the compression portion.

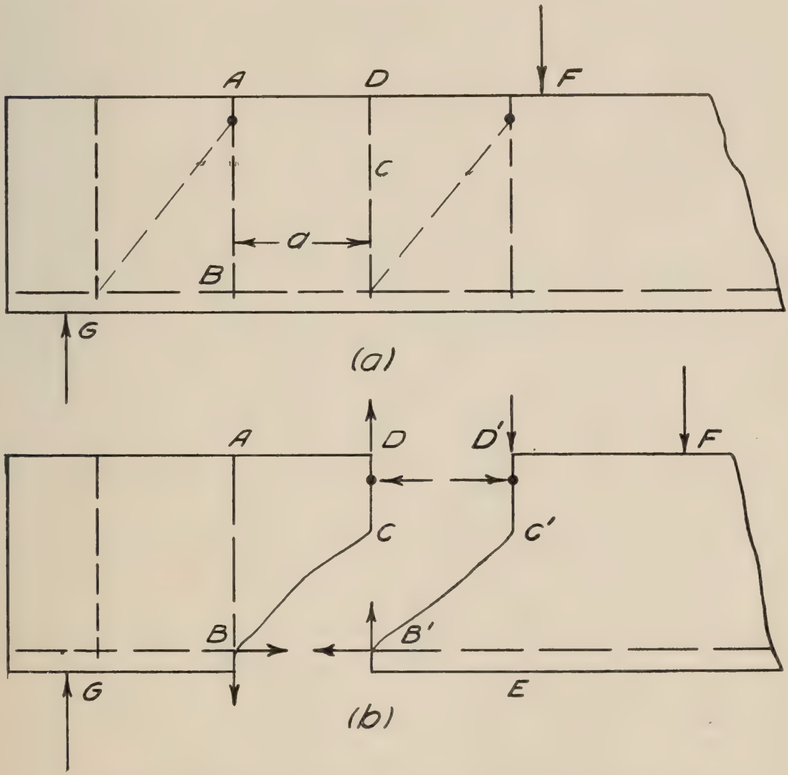

FIG. 5. ACTION OF FORCES IN BEAMS WITH STIRRUPS.

However, as the proportion taken by the stirrups is unknown, it will be assumed in the calculations in this bulletin that all of the shear is taken by the stirrups. This use of equation (21) is somewhat empirical, but it makes a common basis of comparison.

The distribution of bond stresses developed on the surface of the stirrups is indeterminate. Evidently it must not be expected that tension will be transferred to the concrete until the compression area of the beam is reached, or until a point but little below is reached. In the calculation for bond in stirrups in this bulletin, the bond surface of the stirrups for a depth of beam equal to 0.6 d will be arbitrarily assumed.

II. Materials, Test Pieces, and Method of Testing.

12. *Materials.*—The materials used in making the test beams were similar to those used in the reinforced concrete beams described in Bulletin No. 4 and Bulletin No. 14; they may be considered to be representative of the best materials used for this class of work in this section of the country. The stone, sand, and much of the cement were bought in the open market. The Universal portland cement, used in some of the beams, was furnished by the makers. The mild steel rods used for reinforcement were furnished by the Illinois Steel Co. The corrugated bars were supplied by the St. Louis Expanded Metal and Corrugated Bar Co. A form of reinforcement known as the Cummings' unit frame was furnished by Mr. Robert Cummings of Pittsburg, Pennsylvania.

TABLE 1.

Mechanical Analysis of Stone.

Series of 1908.

Size of Mesh inches	Per cent Passing
1	100
$\frac{3}{4}$	93
$\frac{1}{2}$	64
$\frac{3}{8}$	41
$\frac{1}{8}$	22
$\frac{1}{5}$	4
$\frac{1}{10}$	2

TABLE 2.

Mechanical Analysis of Sand.

Sieve No.	Separation Size inches	Per cent Passing	
		1907	1908
3	——	——	98
5	.174	100	87
10	.091	81	63
18	.043	53	37
30	.027	35	20
40	.019	24	11
50	.013	14	4
74	.009	7	2
150	——	2	1

TABLE 3.

Tensile Strength of Cement.

Ref. No.	Ultimate Strength, lb. per sq. in.							
	Chicago AA Cement				Universal Cement			
	Age 7 days		Age 28 days		Age 7 days		Age 28 days	
	Neat	1-3	Neat	1-3	Neat	1-3	Neat	1-3
	Series of 1907							
1	786	230	811	265	410	187	680	370
2	683	145	851	235	470	200	670	330
3	760	218	861	225	360	120	560	360
4	786	186	760	270	405	145	570	290
5	866	215	965	265	320	195	600	295
6	815	211	935	287	310	180	620	310
Av.	783	201	864	258	379	171	617	326
	Series of 1908							
1	559	145	707	247	565	244	764	319
2	732	192	857	318	809	248	885	336
3	665	175	779	266	728	232	776	285
4	811	227	833	307	699	242	754	292
5	666	182	792	284	702	229	763	315
6	693	191	781	283				
7	719	206	767	303				
Av.	692	188	788	287	701	239	788	309

These tests were made with standard Ottawa sand. Tests from one sample of the 1908 cement on briquettes made with natural sand gave a higher strength than did the briquettes made with the standard sand.

Each of the above values is the average of 5 briquettes

TABLE 4.

MECHANICAL ANALYSIS OF CEMENT.

1907			1908		
Sieve No.	Per cent Passing		Sieve No.	Per cent Passing	
	Universal	Chicago AA		Universal	Chicago AA
74	98.6	96.4	74	99.3	98.2
100	96.2	91.2	100	98.5	95.0
200	80.9	69.8	200	90.1	80.6

TABLE 5.

TENSION TESTS OF STEEL.

Series of 1907.

Beam No.	Nominal Size inches	Yield Point lb. per sq. in.	Ultimate Str'ngth lb. per sq. in.	Per cent Elongation in 8 in.	Beam No.	Nominal Size inches	Yield Point lb. per sq. in.	Ultimate Str'ngth lb. per sq. in.	Per cent Elongation in 8 in.
211.1	$\frac{3}{4}$	36 800	56 100	33	416.5	$\frac{1}{2}$	40 700	52 500	29.7
211.2	$\frac{1}{2}$	39 800	55 900	29	416.6	“	40 000	54 800	30
212.1	“	39 700	55 700	29	511.1	“	40 100	54 900	31.5
212.2	“	40 200	56 400	30.5	511.2	“	37 400	53 500	29.5
212.5	“	39 600	54 700	29	512.1	“	39 600	58 900	28
212.6	“	39 900	55 700	28.5	512.2	“	37 300	54 800	29
613.2	“	39 300	54 400	29	531.1	$\frac{5}{8}$	37 400	51 900	31.5
616.2	“	41 000	55 900	29.3	531.2	“	38 400	56 500	31.5
417.5	$\frac{5}{8}$	38 700	54 900	31.5	513.1	$\frac{1}{2}$	38 800	53 400	29.5
417.6	“	39 300	55 700	31	551.2	“	39 400	57 200	28.5
611.1	“	37 200	54 600	30.5	553.1	“	63 200	97 100	9.5
611.2	“	40 500	53 800	30	231.5	“	60 800	94 700	8.5
612.1	“	37 000	51 300	32	232.5	“	52 000	82 300	11
612.2	“	39 200	53 200	31.5	232.6	“	57 200	89 300	10
613.1	“	38 400	54 800	32	233.5	“	58 500	88 100	14.2
616.1	“	38 700	59 600	31.5	233.6	“	64 400	102 500	7.2
617.1	“	38 300	52 500	31.5	233.7	“	57 600	90 900	10.5
213.1	$\frac{1}{2}$	40 700	53 000	30	235.2	“	53 100	86 300	11
213.2	“	39 100	56 000	29.5	235.5	“	64 000	101 500	7
414.5	“	38 700	54 100	30.2	235.6	“	60 000	98 000	11
414.6	“	39 200	54 500	29.2	241.5	“	51 700	84 500	12
214.1	“	39 900	53 500	29.5	221.1	$\frac{3}{4}$	39 000	56 400	32
214.2	“	39 200	52 500	31.5	221.2	“	43 100	64 300	29
415.1	“	40 200	54 000	30.2	223.6	$\frac{1}{2}$	39 100	56 300	29.5
415.2	“	40 100	55 800	29.5	225.5	$\frac{3}{4}$	37 500	57 000	31
415.5	“	40 400	55 800	30.2	227.5	“	40 500	58 000	30
415.6	“	40 400	57 300	28.2	227.6	“	38 500	60 000	30.5
215.1	“	42 100	56 200	30	228.5	“	38 700	61 500	31
215.2	“	43 900	58 100	30.5	228.6	“	39 800	63 100	30

TABLE 5—*Continued.*

TENSION TESTS OF STEEL.

Series of 1908.

Beam No.	Nominal Size inches	Yield Point lb. per sq. in.	Ultimate Str'ngth lb. per sq. in.	Per cent Elongation in 8 in.	Beam No.	Nominal Size inches	Yield Point lb. per sq. in.	Ultimate Str'ngth lb. per sq. in.	Per cent Elongation in 8 in.
210.1	½	40 000	61 200	28.5	336.2	½	40 000	61 000	27
210.3	"	38 700	59 000	29.3	336.2	"	41 600	63 000	27
210.2	"	41 100	61 800	29	336.2	"	40 300	60 700	28
210.2	"	42 200	62 700	28	336.3	"	40 300	60 600	27.4
343.2	"	40 100	59 900	28.6	213.3	"	39 100	61 500	29.5
341.3	"	40 300	60 700	29	213.4	"	39 000	60 100	31
341.3	"	41 000	59 800	29	351.2	"	40 000	61 000	27.7
341.3	"	41 600	64 000	26	214.3	"	39 800	62 500	26.5
341.3	"	40 300	63 500	29	214.4	"	39 400	59 300	28.5
211.4	"	40 200	62 600	28.5	214.5	"	41 100	61 800	28.0
211.5	"	40 200	61 300	29	352.1	"	41 900	62 200	28.0
331.1	"	42 500	63 600	27	352.2	"	40 900	61 300	28
331.3	"	40 800	60 700	29.3	353.2	"	39 200	59 500	28
332.1	"	40 500	57 900	26	351.1	"	40 800	60 900	28.5
217.0	"	39 700	62 500	29	215.3	"	39 600	59 500	29.5
217.1	"	39 900	63 800	26.5	215.4	"	40 500	61 400	27
217.3	"	39 900	61 600	29	361.1	"	39 900	61 300	27.5
217.5	"	40 900	60 700	29.5	362.1	"	40 200	61 000	28
217.2	"	38 200	61 100	30	362.2	"	40 300	61 200	27.5
217.4	"	41 200	62 000	28	363.2	"	40 300	60 300	28
217.4	"	40 000	61 000	29	361.2	"	40 400	61 300	27.5
218.1	"	40 800	61 200	29	363.1	"	40 200	61 000	30.2
218.1	"	39 300	62 300	29	221.3	¾	37 900	58 300	32
218.2	"	40 400	61 700	29.5	221.4	"	37 100	60 100	30.5
218.3	"	40 900	60 600	27.5	223.2	½	41 300	61 000	28.5
218.3	"	40 400	60 500	28.5	223.3	"	40 900	60 500	29
254.1	"	40 400	61 800	29.4	229.1	"	41 100	60 000	28.3
252.5	"	52 800	88 600	15	229.2	"	41 500	63 300	28
252.6	"	51 400	84 800	18	229.2	"	40 600	61 200	27
252.7	"	45 600	77 900	19.5	229.4	"	39 400	61 200	27.5
253.5	"	48 700	83 000	16.2	229.5	"	41 500	61 100	27.5
253.6	"	49 400	80 000	19	229.7	"	40 200	60 500	29
219.1	"	39 300	59 500	27.7	229.8	"	40 300	60 500	29
219.2	"	40 600	61 700	27.3	229.8	"	37 500	61 200	27
255.1	¾	38 000	60 600	33	229.8	"	37 600	59 400	27
255.2	½	41 000	60 800	28.6	233.3	"	40 500	60 600	26.5
220.5	1	39 200	64 500	30	233.4	"	49 400	80 800	21.5
220.1	¾	36 900	63 100	35.5	241.1	"	51 000	84 000	13
220.2	"	36 500	60 300	30	241.2	"	47 500	79 100	20.3
256.1	"	38 600	61 400	29.5	241.7	¾	42 200	60 700	33
256.2	"	38 100	61 100	31.2	241.8	"	45 000	62 600	30
253.1	"	53 400	89 100	11.5	243.3	½	50 100	81 800	18
336.2	½	40 300	61 300	29	243.4	"	36 100	56 400	26

Stone. The stone was a good quality of crushed limestone from Kankakee, Illinois, ordered screened through a 1-in. and

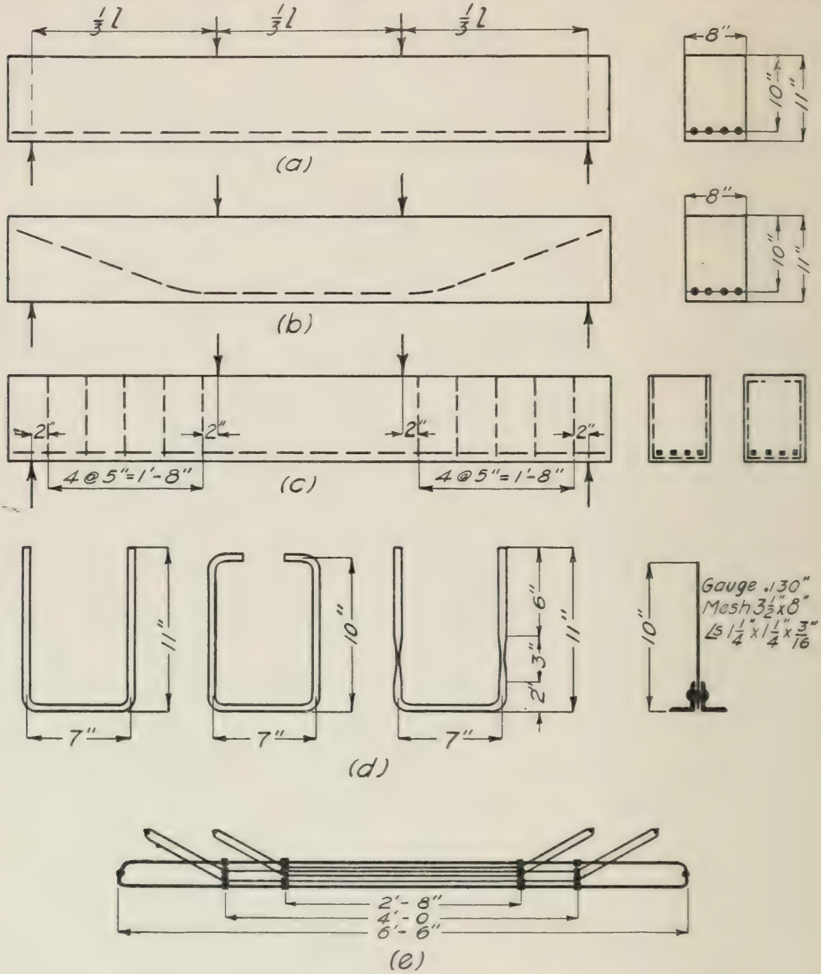

FIG. 6. DETAILS AND ARRANGEMENT OF REINFORCEMENT.

over a ¼-in. screen. It contained about 50 % voids and weighed about 81 lb. per cu. ft. In the determination of the voids in both stone and sand, the material was poured slowly into water to obviate the retention of air. Table 1 gives the average of the tests of 19 samples of the stone used in 1908.

Sand. The sand was of good quality, sharp, well graded, and generally clean; it weighed 104 lb. per cu. ft. loose. Table 2 gives the results of mechanical analyses of this sand.

Cement. Tests of the two brands of cement used for the two years are given in Table 3. Table 4 gives analyses of the fineness.

Concrete. Men accustomed to mixing concrete and making test beams were employed in the work. Care was taken in measuring, mixing, and tamping to secure as uniform a concrete as possible. All materials were proportioned by loose volume, and weights were taken as a check on the measurement. The mixing was done with shovels by hand. The sand and cement were first mixed dry; the stone, which had previously been thoroughly moistened, was added and the mass then turned until of a uniform appearance. Water was then added in such proportion as to give a fairly wet mixture. The mass was again turned until thoroughly mixed.

Steel. The steel reinforcing bars consisted of plain round rods and deformed bars. The round rods were open hearth mild steel. The deformed bars were square corrugated bars with "new style" corrugations. Two grades of the deformed bars were used, one of mild steel for some of the stirrups and one of high elastic limit. Test pieces were cut from all the reinforcing bars used. Table 5 gives the results of the tests. In those beams which failed by tension in the steel individual results are recorded. In those in which the tensile strength of the steel was not developed the average of all tests for the several sizes is given. Tests of Cummings' reinforcement showed the yield point of the steel to be about 44 000 lb. per sq. in.

13. *Test Beams.*—In all the tests herein described, the cross-section of the beams was 8 x 11 in., the center of the longitudinal reinforcement being placed 10 in. below the top surface throughout at least the middle third of the length of the beam. The span length varied from 6 ft. to 12 ft. The total length of the beam was 6 in. more than the span length in the beams of 6 ft. span length, and 12 in. more in the 12 ft. lengths. In a large proportion of the beams, the reinforcing bars were straight from end to end. In the beams with bars bent up, the bending of the bars began at a point about 3 in. outside the load point and passed diagonally in a slightly curved line to a point 2½ in. or 5 in. from the top of the

beam over the supports. The general position and disposition of the bars are shown in Fig. 6, and the details are given in Tables 8, 11, and 13. The arrangement of nuts and washers at the end of the bars and of hooked ends, as used in some of the beams, is shown in Fig. 14 and 18.

Included in the beams with bars bent up are those made with the Cummings' unit frame. This reinforcement (see Fig. 6) consisted of two $\frac{5}{8}$-in. round rods carried straight to a point beyond the supports and there bent and welded to form a loop near the end of the beam, one pair of $\frac{3}{8}$-in. round rods bent up diagonally at the one-sixth point and looped and welded near the top of the beam, and another pair of $\frac{3}{8}$-in. round rods bent up at a point 8 inches from the one-sixth point. These rods were connected laterally with the $\frac{5}{8}$-in. rods at the points of bending by means of steel plates.

In beams with stirrups, the stirrups were U-shaped and passed under the longitudinal bars and extended to the top of the beam. In some beams the stirrups were left too close to the side of the beam to be effective. Fig. 6 shows the shape of the stirrups and their general spacing, and Fig. 16, 17 and 18 show the arrangement for individual beams. The size and spacing of the stirrups are given in Table 13. The stirrups were placed in the outer thirds of the beams, except that in Beams No. 229.1, 229.2, 229.5 and 229.8 stirrups were placed in one end only. The stirrups in Beams No. 222.5, 222.6, 224.5 and 224.6 were tapered to a reduced section, as shown in Fig. 6. The longitudinal reinforcing bars were straight, except in Beam No. 229.8, in which two bars were bent up in the end not having stirrups.

Two beams were reinforced with two small angles riveted together and holding between them a web of expanded metal which extended up to the top of the beam. This form of reinforcement was used by the company furnishing it. The arrangement is shown in Fig. 6.

For general data of beams see Table 8, p. 34, Table 11, p. 35, and Table 13, p. 62.

14. *Making of the Beams.*—The beams were made in a manner similar to that described in Bulletin No. 14. They were built directly on the concrete floor of the laboratory with a strip of building paper beneath the forms. The forms were generally removed

after seven days, but the beams were not moved until the date of test.

15. *Minor Test Pieces.*—In many cases tests were made on 6-in. cubes from the batch of concrete used in the beams. The results are given in Table 6. In addition to this a flexure test was made of a plain concrete control beam or check beam to give a means of judging of the resistance of the concrete to tension. These control beams were 6 x 8 x 40 in. and were tested with a 3-ft. span and one-third point loading. In testing, they were placed on a wooden base, so arranged as to insure a good distribution of the loads and pressures across the width of the beam, the wood acting as a cushion and permitting adjustment for any warped condition of the beam. The results of these tests are given in Tables 9, 10, and 12.

16. *Storage.*—The beams were left on the floor of the mixing

TABLE 6.

Compression Tests of 6-in. Cubes.

Series of 1907.

No.	Kind of Concrete	Age at Test days	Maximum Load lb. per sq. in.	No.	Kind of Concrete	Age at Test days	Maximum Load lb. per sq. in.
211.1	1-1½-3	352	5080	224.5	1-2-4	303	1960
211.1	"	"	5340	224.6	1-2-4	267	2110
211.1	"	"	3640	225.7	1-2-4	332	3730
211.1	"	359	4310	225.7	"	336	3400
212.5	1-2-4	357	3610	225.7	"	"	3240
212.5	"	359	3680	227.5	1-2-4	313	4170
212.5	"	"	3200	227.5	"	316	3842
212.5	"	"	3100	227.5	"	318	4110
212.5	"	"	2870	235.6	1-5-10	334	1165
214.1	1-4-8	342	1370	235.6	"	"	1150
214.1	"	344	1260	241.6	1-2-4	317	3300
217.5	1-2-4	303	1960	241.6	"	325	3120
221.1	1-2-4	334	2570	241.6	"	"	3030
221.6	1-2-4	323	2530	271.6	1-2-4	317	3300
222.6	1-2-4	267	2110	271 6	"	325	3120
223.6	1-2-4	313	4170	271 6	"	"	3030
223.6	"	316	3842	417 6	1-2-4	303	2420
223.6	"	318	4110	521 5	1-2-4	323	2530

TABLE 6—*Continued.*

COMPRESSION TESTS OF 6-IN. CUBES.

Series of 1908.

No.	Kind of Concrete	Ages at Test days	Maximum Load lb. per sq. in.	No.	Kind of Concrete	Age at Test days	Maximum Load lb. per sq. in.
210.1	1–1–2	65	4045	217.5	1–2–4	75	1537
210.1	"	"	3995	217.5	"	"	1692
210.1	"	"	3835	217.5	"	"	1731
210.2	1–1–2	70	5715	218.2	1–2–4	59	2583
210.2	,,	"	4670	218.2	"	"	2650
210.2	,,	"	5180	218.2	"	"	2778
210.3	1–1–2	63	3520	218.3	1–2–4	60	2700
210.3	"	"	3560	218.3	"	"	2240
210.3	"	"	3620	218.3	"	"	2620
211.4	1–1½–3	65	3275	218.4	1–2–4	68	1970
211.4	"	"	3080	218.4	"	"	1725
211.4	"	"	3590	218.4	"	"	1870
213.3	1–3–6	65	1722	219.2	1–2–4	59	2583
213.3	"	"	1752	219.2	"	"	2650
213.3	"	"	1590	219.2	"	"	2778
213.4	1–3–6	65	1130	220.2	1–2–4	59	2392
213.4	"	"	1034	220.2	"	"	2270
213.4	"	"	1192	220.2	"	"	2322
214.4	1–4–8	68	1297	220.5	1–2–4	67	2370
214.4	"	"	1364	220.5	"	"	2150
214.4	"	"	1255	220.5	"	"	2110
215.3	1–5–10	64	1075	221.3	1–2–4	57	2672
215.3	"	"	1075	221.3	"	"	2450
215.3	"	"	1143	221.3	"	"	2735
215.4	1–5–10	69	1227	221.4	1–2–4	62	1810
215.4	"	"	1218	221.4	"	"	1890
215.4	"	"	1080	221.4	"	"	1660
215.5	1–5–10	60	942	223.2	1–2–4	57	2672
215.5	"	"	892	223.2	"	"	2450
215.5	"	"	872	223.2	"	"	2735
217.0	1–2–4	61	2980	223.3	1–2–4	62	1810
217.0	"	"	3340	223.3	"	"	1890
217.0	"	"	2670	223.3	"	"	1660
217.1	1–2–4	15	1310	229.1	1–2–4	61	2980
217.1	"	"	1135	229.1	"	"	3340
217.1	"	"	1140	229.1	"	"	2670
217.2	1–2–4	66	2330	229.2	1–2–4	83	3140
217.2	"	"	2100	229.2	"	"	2850
217.2	"	"	2070	229.2	"	"	3250
217.4	1–2–4	69	2880	229.5	1–2–4	75	1537
217.4	"	"	2900	229.5	"	"	1692
217.4	"	"	2960	229.5	"	"	1731

TABLE 6—*Continued.*

COMPRESSION TESTS OF 6-IN. CUBES.

Series of 1908.

No.	Kind of Concrete	Age at Test days	Maximum Load lb. per sq. in.	No.	Kind of Concrete	Age at Test days	Maximum Load lb. per sq. in.
233.3	1–2–4	74	1700	331.3	1–2–4	34	391
233.3	"	"	1520	331.3	"	"	410
233.3	"	"	1410	331.3	"	"	420
240.1	1–2–4	62	2750	332.1	1–2–4	11	1420
240.1	"	"	2490	332.1	"	"	1510
240.1	"	"	2580	332.1	"	"	1620
240.2	1–2–4	59	1770	333.1	1–2–4	17	626
240.2	"	"	1810	333.1	"	"	640
240.2	"	"	1770	333.1	"	"	738
243.3	1–2–4	62	2750	342.2	1–1–2	69	3880
243.3	"	"	2490	342.2	"	"	4030
243.3	"	"	2580	342.2	"	"	3640
252.6	1–2–4	59	2392	351.1	1–4–8	202	1420
252.6	"	"	2270	351.1	"	"	1131
252.6	"	"	2322	351.1	"	"	1232
252.7	1–2–4	59	3008	351.2	1–4–8	14	828
252.7	"	"	3194	351.2	"	"	752
252.7	"	"	2964	251.2	"	"	866
253.1	1–2–4	59	2392	352.1	1–4–8	62	1490
253.1	"	"	2270	352.1	"	"	1620
253.1	"	"	2322	352.1	"	"	1610
253.5	1–2–4	65	3480	352.2	1–4–8	63	1028
253.5	"	"	3730	352.2	"	"	997
253.5	"	"	3770	352.2	"	"	1000
253.6	1–2–4	59	3008	353.2	1–4–8	68	831
253.6	"	"	3194	353.2	"	"	745
253.6	"	"	2964	353.2	"	"	884
254.1	1–2–4	67	2025	361.1	1–5–10	49	1050
254.1	"	"	2160	361.1	"	"	1040
254.1	"	"	2125	361.1	"	"	985
255.1	1–2–4	68	2360	362.1	1–5–10	60	842
255.1	"	"	2300	362.1	"	"	937
255.1	"	"	2040	362.1	"	"	832
255.2	1–2–4	61	2430	362.2	1–5–10	69	1010
255.2	"	"	2475	362 2	"	"	820
255.2	"	"	2470	362.2	"	"	862
256.1	1–2–4	68	2360	363.1	1–5–10	184	733
256.1	"	"	2300	363.1	"	"	720
256.1	"	"	2040	363.1	"	"	1005
256.2	1–2–4	61	2430	363.2	1–5–10	68	570
256.2	"	"	2475	363.2	"	"	598
256.2	"	"	2470	363.2	"	"	640
331.1	1–2–4	6	776				
331.1	"	"	834				
331.1	"	"	897				

room until the date of test, when they were removed to the Materials Testing Laboratory. They were dampened occasionally to prevent too rapid drying. The temperature ranged from 55° to 70° F. Owing to incompleteness of the heating arrangement, the temperature of the room during the early part of the period of making beams in 1907 was less uniform than could have been desired, and the beams first made probably did not have as favorable conditions for setting as would usually be the case.

17. *Method of Testing.*—In testing, the beams were loaded at the one-third points, as described in Bulletin No. 4, page 34, except that in Beams No. 229.1, 229.2 and 229.5 a single load was applied at the one-third point next to the end having the stirrups. The beams were all tested in the 200 000-lb. Olsen testing machine. The bedding of the plates and the facilities for longitudinal adjustment in the test were the same as those in the earlier tests.

Center deflections were read on all the beams. Deformations of the upper fiber and steel were measured on only part of the beams; the discussion of this part of the work is left for a later bulletin. The methods of measuring the deflections and deformations are fully described in Bulletin No. 4.

III. Experimental Data and Discussion.

18. *Explanation of Tables.*—Tables 8, 11, and 13 give data of the make-up of the test beams. Tables 9, 12, and 14 contain data of the tests of the beams. The per cent of cement recorded in the tables is based upon weights and is given in terms of the aggregate (stone and sand) and not of the resulting concrete. The loads given in the tables are the loads applied by the testing machine, and do not include the weight of the beam. The load at first diagonal crack is the load noted when the first diagonal crack was observed. The stress in the longitudinal reinforcement is calculated from the bending moment, taking into account the weight of the beam. In determining the amount of the vertical shearing stress an amount was added to include the effect of the weight of the beam at about the one-sixth point, together with the loading apparatus. In the calculation of stresses, equation (13), p. 6, $M = Afd'$, was used for calculating the stress in longitudinal reinforcement. The vertical shearing unit stress was calculated with equation (18), p. 9, $v = \frac{V}{bd}$, and the bond

unit stress with equation (17), p. 8, $u = \frac{V}{mod'}$. The values of d' were selected with reference to the amount of reinforcement and the modulus of elasticity of the concrete. The moduli for different mixtures and ages had been determined by another investigation, and the values of j (ratio of d' to d) were calculated by the method given in Bulletin No. 4. The values of j used are given in Table 7. In all cases, whether the bars were bent up or not, and whether there were stirrups or not, the foregoing formulas for shearing stresses and bond stresses were used. The term *nominal* shearing stress is employed, as noted on page 18. The modulus of rupture of the control beams was calculated by the usual rectangular beam formula. The stress in the stirrups was calculated by the methods given on page 18. For the bond stress in stirrups the area of stirrup available was considered to be that taken by a length of stirrup equal to six-tenths of the distance from the top of the beam to the center of the reinforcing bars.

TABLE 7.

VALUES OF j USED IN CALCULATIONS.

Kind of Concrete	Reinforcement per cent	Age, days			
		7	14	30	60
1-1-2	1.00	.825	.845	.865	.87
1-1½-3	1.00		.84		.865
“	1.65				.84
1-2-4	1.00	.80	.825	.845	.85
“	1.25				.84
“	1.30				.835
“	1.50				.83
“	1.65				.825
“	1.96				.82
“	2.20				.81
“	2.81				.80
1-3-6	1.00				.845
1-4-8	1.00		.80	.825	.84
1-5-10	1.00				.825
“	1.25				.82

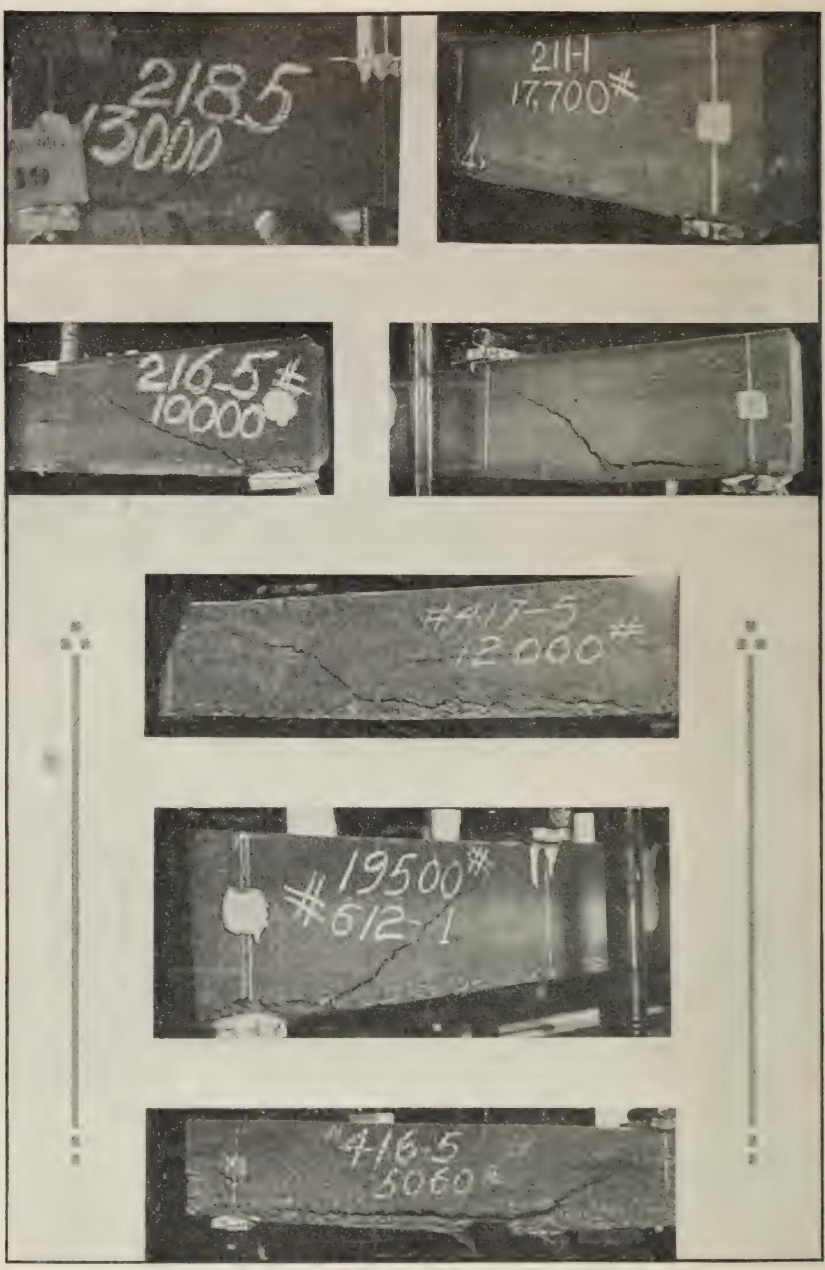

Fig. 7. Views of Beams after Test.

19. *Deflection Diagrams.*—Diagrams showing the center deflections of the various beams for the applied loads are given in Fig. 19 to 25 at the end of the text.

A. BEAMS WITHOUT WEB REINFORCEMENT.

20. *Beams without Web Reinforcement.*—In beams without web reinforcement which fail by diagonal tension, the first sign of approaching failure to be noted is a small diagonal crack generally found somewhat below the middle of the depth of the beam at a point about half way between the load point and the end support. Sometimes it seems to start at the level of the reinforcing bars, or is not noted until it has extended that far down, running from a vertical crack which has already formed up to that level. As the load on the beam is increased, the crack lengthens and extends from the level of the reinforcing bar diagonally upward, reaching the load point or to within a few inches of the load point at or near the maximum load carried. The angle which the crack makes with the horizontal and its position with reference to the support and load point depend upon the strength of the concrete forming the web, upon the length or slenderness of the beam, and upon the amount of reinforcement.

In one or two cases the crack extended diagonally from the support to the load point. In many beams a longitudinal crack formed along the upper level of the reinforcing bars toward the support, the bars stripping off from the concrete above by the action of vertical tension. The views in Fig. 7 show various forms of cracks in beams of the 1907 series. The characteristics of these cracks will be taken up farther on. Generally the beam finally carried a load greater than that applied when the diagonal crack was first noted, but in many of the beams no crack was noted until the maximum load was reached, and then failure along this diagonal crack was sudden and complete. In general, after the maximum load was reached, the load fell off at once, and a dead load would have produced instant failure.

The disposition of bars used in this group (no bars bent up and no stirrups) permits a comparison of the resistance of the concrete to diagonal tension without the complication which would otherwise exist. As the bars extended beyond the beam supports (1½ in. in the 6-ft. span, and 3 in. in the 12-ft. span), there is a some-

TABLE 8.

DATA OF BEAMS WITHOUT WEB REINFORCEMENT.

Series of 1907.

Beam No.	Kind of Concrete	Cement		Reinforcement		Span Length feet
		Kind	Per cent	Description	Per cent	
218.5	1-1½-3	U	18.8	4 ½-in. round	0.98	6
218.6	do.	U	18.8	do.	0.98	6
211.3	1-1½-3	AA	20.6	4 ½-in. round	0.98	6
211.1	do.	AA	22.2	3 ¾-in. round	1.65	6
211.2	do.	AA	21.1	do.	1.65	6
216.1	1-2-4	AA	15.7	4 ½-in. round	0.98	6
216.2	do.	AA	14.6	do.	0.98	6
216.5	do.	U	15.9	do.	0.98	6
216.6	do.	U	10.6	do.	0.98	6
217.5_1	1-2-4	U	15.9	4 ½-in. round	0.98	6
217.6	do.	U	10.6	do.	0.98	6
217.5_2	do.	U	15.7	do.	0.98	6
212.7	1-2-4	U	15.4	4 ½-in. round	0.98	6
212.1	1-2-4	AA	16.1	5 ½-in. round	1.23	6
212.2	do.	AA	15.3	do.	1.23	6
212.5	do.	U	15.1	do.	1.23	6
212.6	do.	U	15.5	do.	1.23	6
613 2	do.	AA	13.4	do.	1.23	6
616.2	do.	AA		do.	1.23	6
251.1	do.	AA	14.6	4 ½-in. cor.	1.25	6
251.2	do.	AA	17.5	do.	1.25	6
251.3	do.	AA	14.3	do.	1.25	6
251.4	do.	AA	14.3	do.	1.25	6
417.5	1-2-4	U	15.6	4 ⅝-in. round	1.53	12
417.6	do.	U	15.6	do.	1.53	12
611.1	1-2-4	AA	15.5	4 ⅝-in. round	1.53	6
611.2	do.	AA	15.8	do.	1.53	6
612.1	do.	AA	15.4	do.	1.53	6
612.2	do.	AA	15.8	do.	1.53	6
613.1	do.	AA	15.4	do.	1.53	6
616.1	do.	AA	15.8	do.	1.53	6
617.1	do.	AA	16.0	do.	1.53	6
617.2	do.	AA	15 5	do.	1.53	6
213.1	1-3-6	AA	10.7	4 ½-in. round	0.98	6
213.2	do.	AA	10.3	do.	0.98	6
414.5	do.	U	11.2	do.	0.98	12
414.6	do.	U	13.0	do.	0.98	12
214.1	1-4-8	AA	8.4	do.	0.98	6
214.2	do.	AA	8.5	do.	0.98	6
415.1	do.	AA	8.2	do.	0.98	12
415.2	do.	AA	7.1	do.	0.98	12
415.5	do.	U	8.0	do.	0.98	12
415.6	do.	U	8.0	do.	0.98	12
215.1	1-5-10	AA	6.5	4 ½-in. round	0.98	6
215.2	do.	AA	6.5	do.	0.98	6
416.5	do.	U	6.4	do.	0.98	12
416.6	do.	U	5.7	do.	0.98	12

[Continued on page 36.

TABLE 9.

TESTS OF BEAMS WITHOUT WEB REINFORCEMENT.

Series of 1907.

All beams failed by diagonal tension unless otherwise noted.

Beam No.	Age days	Load at First Diagonal Crack pounds	Maximum Applied Load pounds	Stress in Longi'nal Reinforcement lb. per sq.in.	Vertical Shearing Stress lb. per sq. in.	Bond Stress lb. per sq. in.	Control Beam	
							Modulus of Rupture lb. per sq.in.	Age days
218.5	14	12 000	13 000	24 500	103	139	248	14
218.6	14	12 000	14 900	27 900	114	148	248	14
211.3	61	18 000	19 100	34 300	144	194	354	61
211.1	63	18 000	29 000	31 800	222	251	331	61
211.2	67	15 000	18 300	20 200	142	160	310	57
216.1	7	......	9 000	18 000	71	95	223	62
216.2	7	6 000	6 000	12 300	54	73	135	10
216.5	9	10 000	10 000	19 900	86	116	202	10
216.6	8	8 900	8 900	17 800	76	103	137	10
217.5_2	14	11 000	11 600	22 300	94	127	202	10
217.6	14	12 000	12 000	23 100	97	131	138	10
217.5_1	25	12 000	14 600	27 200	114	154	147	23
212.7	60	18 100	18 100	33 400	138	186	336	77
212.1	63	19 000	20 000	29 700	155	167	228	61
212.2	59	14 000	20 900	31 000	162	175	305	57
212 5	64	14 000	15 400	23 000	121	131	221	61
212.6	61	14 000	17 000	25 300	132	143	246	57
613.2	61	18 000	18 500	27 500	144	156	280	94
616.2	63	20 000	24 700	36 500	190	205	260	94
251.1	60	19 200	19 200	28 100	149	149	291	63
251.2	60	14 500	14 500	21 300	114	114	183	61
251.3	60	12 300	12 800	18 800	102	102	238	61
251.4	60	14 000	14 000	20 600	110	110	288	61
417.5	61	......	12 000	30 400	100	102	229	62
417.6	63	.....	10 500	26 800	89	91	189	63
611.1	57	16 000	19 000	22 900	149	152	293	60
611.2	61	22 400	22 400	27 000	175	178	252	55
612.1	57	10 000	19 500	23 500	153	156	339	60
612.2	61	14 000	18 450	22 200	145	148		
613.1	57	12 000	14 000	17 000	111	113	307	60
616.1	60	18 000	20 000	24 100	156	159	249	64
617.1	62	16 000	21 700	26 100	169	172	304	61
617.2	57	18 000	22 250	26 800	173	176	304	60
213.1	63	9 000	12 400	23 100	98	132	178	60
213.2	57	11 000	11 400	21 300	90	121	204	65
414.5	59	...	7 920	31 600	69	93		
414.6	61	......	8 430	33 500	72	97		
214.1	62	11 000	11 300	21 200	90	121	179	56
214.2	57	9 500	9 500	17 900	77	104	174	57
415.1	75	......	8 680	34 300	75	101	135	78
415.2	62	.....	7 220	29 000	64	86	188	87
415.5	57	......	7 000	28 300	62	84	151	63
415.6	62	......	8 000	30 400	70	95	125	63
215.1	62	10 000	10 200	19 100	84	113	174	56
215.2	61	8 000	8 600	19 900	72	97		
416.5	65	......	5 060	21 300	49	66	109	61
416.6	70	......	5 830	24 100	54	73	118	63

[Continued on page 37.

TABLE 8.—*Continued.*

DATA OF BEAMS WITHOUT WEB REINFORCEMENT.

Series of 1908.

Beam No.	Kind of Concrete	Cement		Reinforcement		Span Length feet
		Kind	Per cent	Description	Per cent	
210.1	1–1–2	AA	28.5	4 ½-in. round	0.98	6
210.3	do.	AA	30.7	do.	0.98	6
210.2	do.	AA	29.6	do.	0.98	6
343.2	do.	AA	29.8	6 ½-in. round	1.47	12
341.3	do.	AA	30.1	4 ½-in. round	0.98	12
211.4	1–1½–3	AA	19.8	4 ½-in. round	0.98	6
211.5	do.	AA	19.5	do.	0.98	6
331.1	1–2–4	AA	15.7	4 ½-in. round	0.98	12
331.3	do.	AA	14.9	do.	0.98	12
332.1	do.	AA	15.3	do.	0.98	12
217.0	1–2–4	AA	15.3	4 ½-in. round	0.98	6
217.1	do.	AA	14.9	do.	0.98	6
333.1	do.	AA	14.5	do.	0.98	12
217.3	1–2–4	AA	16.5	4 ½-in. round	0.98	6
217.5	do.	AA	14.3	do.	0.98	6
217.2	1–2–4	AA	14.9	4 ½-in. round	0.98	6
217.4	do.	AA	14.4	do.	0.98	6
218.1	do.	AA	14.7	do.	0.98	6
218.2	do.	AA	14.7	do.	0.98	6
218.3	do.	AA	15.1	do.	0.98	6
218.4	do.	AA	15.1	do.	0.98	6
254.1	do.	AA	14.3	5 ½-in. round	1.23	8
254.2	do.	AA	15.3	do.	1.23	8
252.5	1–2–4	U	15.0	4 ½-in. cor. h. s.	1.25	6
252.6	do.	AA	14.7	do.	1.25	6
252.7	do.	U	14.6	do.	1.25	6
253.5	do.	U	14.5	do.	1.25	12
253.6	do.	U	14.6	do.	1.25	6
219.1	1–2–4	AA	14.7	6 ½-in. round	1.47	6
219.2	do.	AA	14.7	do.	1.47	6
240.2	do.	AA	14.2	3 ¾-in. round*	1.65	6
255.1	do.	AA	15.3	3 ¾-in. round	1.65	10
255.2	do.	AA	13.4	7 ½-in. round	1.71	10
220.5	do.	U	14.1	2 1-in. round	1.96	6
220.1	do.	AA	16.5	4 ¾-in. round	2.21	6
220.2	do.	AA	14.1	do.	2.21	6
256.1	do.	AA	14.2	do.	2.21	12
256.2	do.	AA	14.6	do.	2.21	12
253.1	do.	AA	14.7	4 ¾-in. cor. h. s.	2.81	12
336.3	do.	AA	14.5	5 ½-in. round	1.23	12
213.3	1–3–6	AA	11.0	4 ½-in. round	0.98	6
213.4	do.	AA	9.5	do.	0.98	6
351.2	1–4–8	AA	7.3	do.	0.98	12

*Washers held by nuts on both faces.

[Continued on page 38.

TABLE 9.—*Continued.*

TESTS OF BEAMS WITHOUT WEB REINFORCEMENT.

Series of 1908.

All beams failed by diagonal tension unless otherwise noted.

Beam No.	Age days	Load at First Diagonal Crack pounds	Maximum Applied Load pounds	Stress in Longi'nal Reinforcement lb. per sq. in.	Vertical Shearing Stress lb. per sq. in.	Bond Stress lb. per sq. in.	Control Beam	
							Modulus of Rupture lb. per sq. in.	Age days
210.1	63	25 000	25 640	45 800	190	257	492	61
210.3	60	20 000	24 500	43 800	182	246	390	60
210.2*	72	18 000	31 000	55 300	229	309	553	69
343.2	73	12 000	16 900	41 700	134	121	766	69
341.3*	253	7 600	12 000	45 000	96	130	607	251
211.4	63	16 000	18 800	34 100	142	192	395	68
211.5	72	15 900	24 200	43 700	181	245	448	71
331.1	7	7 000	7 750	33 000	72	97	29	3
331.3	4	2 900	2 900	14 400	33	45	140	11
332.1	7	8 000	8 600	36 300	78	105	213	7
217.0	14	15 400	16 200	30 900	128	173	400	63
217.1	15	13 500	14 000	26 800	111	150	227	15
333.1	17	7 000	7 500	31 000	66	89	157	17
217.3	32	17 900	18 500	34 300	143	193		
217.5	37	13 000	13 600	25 400	107	145	278	75
217.2	63	.....	20 000	36 800	152	205	301	67
217.4*	81	16 000	24 700	45 100	187	252	439	87
218.1*	65	19 000	24 900	45 600	188	254	333	70
218.2	67	19 000	23 000	42 200	175	236	422	61
218.3	60	14 000	16 600	30 600	128	178	445	69
218.4	61	17 000	17 300	31 900	133	180		
254.1	63	16 000	16 740	33 400	132	143		
254.2	75	16 000	22 200	44 000	172	166		
252.5	66	25 000	26 000	37 800	199	199		
252.6	66	20 800	20 800	30 400	161	161	452	72
252.7	64	19 000	23 700	34 500	182	182		
253.5	66	17 000	18 450	55 200	147	147	365	59
253.6	64	......	24 500	35 700	188	188		
219.1	65	25 000	25 200	31 600	193	174	333	70
219.2	67	20 000	21 700	27 200	169	152	422	61
240.2	64	18 000	20 500	23 100	161	182	321	66
255.1	63	16 000	18 900	36 000	151	171	492	64
255.2	63	17 000	20 000	36 700	162	125		
220.5	67	17 000	19 400	18 500	155	98	243	67
220.1	68	23 850	23 850	20 500	190	162		
220.2	66	27 000	27 000	23 000	214	182	427	72
256.1	64	13 000	18 210	31 900	150	128	492	64
256.2	71	18 000	21 000	36 700	172	146	281	64
253.1	67	20 000	21 300	29 700	174	144		
336.3	251	12 000	14 800	45 300	109	111	348	251
213.3	68	20 000	22 150	40 900	170	230	281	68
213.4	67	9 000	13 300	24 900	104	140	197	66
351.2	14	......	3 340	7 200	32	43	97	14

* Tension failure.

[Continued on page 39.

TABLE 8.—*Continued.*

DATA OF BEAMS WITHOUT WEB REINFORCEMENT.

Series of 1908.

Beam No.	Kind of Concrete	Cement		Reinforcement		Span Length feet
		Kind	Per cent	Description	Per cent	
214.3	1–4–8	AA	7.3	4 ½-in. round	0.98	6
214.4	do.	AA	7.7	do.	0.98	6
214.5	do.	AA	7.7	do.	0.98	6
352.1	do.	AA	7.4	do.	0.98	12
352.2	do.	AA	7.5	do.	0.98	12
353.2	do.	AA	7.3	do.	0.98	12
351.1	do.	AA	7.2	do.	0.98	12
215.3	1–5–10	AA	6.5	do.	0.98	6
215.4	do.	AA	6.2	do.	0.98	6
215.5	do.	AA	5.7	do.	0.98	6
361.1	do.	AA	6.8	do.	0.98	12
362.1	do.	AA	6.2	do.	0.98	12
362.2	do.	AA	6.1	do.	0.98	12
363.2	do.	AA	6.1	do.	0.98	12
361.2	do.	AA	6.1	do.	0.98	12
363.1	do.	AA	6.0	do.	0.98	12

what greater area of bar to resist bond stress than is taken into account in the formula. The amount of this is not large and the excess of bond area is less than is generally found in actual reinforced concrete construction; the effect upon calculations of diagonal tension and shear is slight. It should be borne in mind also that in these tests the load was applied by increasing it continuously to failure. It must be expected that repeated applications of a load will have considerable effect upon the resistance of the web to diagonal tension, especially after diagonal cracks have formed. Just what proportion of the load which produces failure in the ordinary test would finally cause failure by repetitive loading is not known. The critical load is probably between that for first crack and the ordinary breaking load.

For reasons already given, the vertical shearing unit-stress will be used as the measure or means of comparison for the resistance of concrete to diagonal tensile stresses, and the values of the vertical shearing stresses are given for this purpose. The test beams were planned to give information along several lines,—(a) the effect of the amount of cement, (b) the effect of the age of the

TABLE 9.—*Continued.*

TESTS OF BEAMS WITHOUT WEB REINFORCEMENT.

Series of 1908.

All beams failed by diagonal tension unless otherwise noted.

Beam No.	Age days	Load at First Diagonal Crack pounds	Maximum Applied Load pounds	Stress in Longi'nal Reinforcement lb. per sq.in.	Vertical Shearing Stress lb. per sq. in.	Bond Stress lb per sq. in.	Control Beam	
							Modulus of Rupture lb. per sq.in.	Age days
214.3	67	14 450	14 450	27 200	113	153	183	67
214.4	72	12 000	13 200	24 800	103	139	140	70
214.5	64	12 000	13 800	26 000	108	146		
352.1	62	7 500	9 100	36 300	78	105	224	62
352.2	65	7 000	7 400	30 100	65	88		
353.2	73	6 600	8 020	32 400	70	95	160	69
351.1	192	7 000	7 000	28 700	62	84	184	192
215.3	66	9 700	9 700	18 800	80	108	132	79
215.4	71	9 700	10 000	19 300	82	111	176	60
215.5	67	8 900	8 900	17 300	74	93	176	60
361.1	67	6 800	6 800	28 400	62	84	173	70
362.1	67	6 700	6 700	28 000	61	82		
362.2	68	4 300	4 300	19 200	43	58	88	70
363.2	73	3 500	3 500	16 200	37	50	94	69
361.2	254	4 600	4 600	19 600	45	61	38	251
363.1	190	8 010	8 010	32 800	72	97	96	62

test beam, (c) the effect of the length of beam as compared with its depth, and (d) the effect of the amount of reinforcement. These topics will be discussed in order, together with the relation of the strength of the beam to that of the auxiliary test pieces and the amount of the load at which the first diagonal cracks were noted. Generally speaking, the beams were planned to give diagonal tension failure. The results of the tests of several beams made for other purposes have been utilized, however, in order to extend the range of the work, even though the failure was not by diagonal tension. Failures other than by diagonal tension are noted in the tables.

21. *Effect of Amount of Cement.*—The purpose of one set of tests was to find the effect upon web resistance of quality of concrete as influenced by amount of cement used. It is evident, of course, that the richness and the strength of the concrete will have a very decided influence on resistance to web stresses. In

Table 9 (p. 35, 37 and 39) are given the values of the vertical shearing stresses for beams having a variety of proportions of cement. The effect of amount of cement upon resistance to diagonal tension in beams of 6-ft. span at an age of about 60 days is brought out in Fig. 8 in which values for 1 % beams of 6-ft. span tested at an age of about 60 days are platted. The general average values of the vertical shearing unit-stress for beams of 6-ft. span about 60 days old for the two years may be stated as follows: 1–1–2 concrete, 180 and 200 lb. per sq. in.; 1–2–4 concrete, 130 and 150 lb. per sq. in., 1–3–6 concrete, 95 and 120 lb. per sq. in.; 1–4–8 concrete, 80 and 110 lb. per sq. in. The results of a wider range of experiments, reduced to values for 1 % reinforcement and 8⅓-ft. span length (span = 10 *d*) by the method which is explained on page 45, are platted in Fig. 12, and are discussed on page 46.

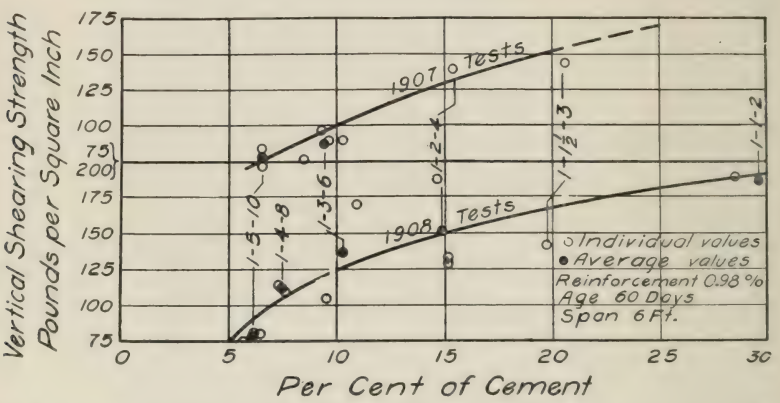

FIG. 8. DIAGRAM SHOWING EFFECT OF AMOUNT OF CEMENT UPON WEB RESISTANCE.

The variation from average values found in individual beams should be noted, and the possibility of such variation suggests the desirability of choosing a lower working stress than would otherwise be necessary. It is evident from these tests that the addition of cement gives a considerable gain in resistance to diagonal tension and that a rich concrete should be used in the web of reinforced concrete beams which are subjected to any considerable amount of diagonal tension, especially if there is no metallic web reinforcement or the web reinforcement is not effective.

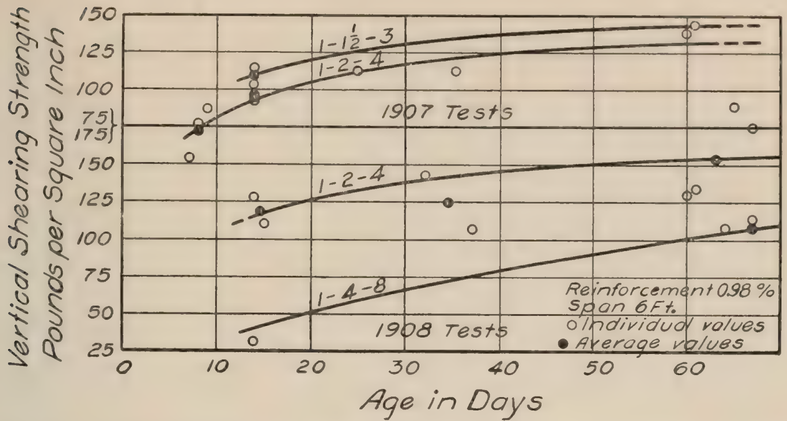

FIG. 9. DIAGRAM SHOWING EFFECT OF AGE UPON WEB RESISTANCE.

22. *Effect of Age.*—It is important to know at what age concrete may be permitted to resist web stresses, as, for example, to know the effect of removal of forms and supports. In Fig. 9 the vertical shearing stress which beams 6-ft. long developed at various ages, taken from Table 9, are platted. These may be expected to represent the web strength of beams of the dimensions used for the temperatures and conditions of the laboratory. The results show considerable variation, as is to be expected. A rapid increase with age may be noted at the earlier ages, and a slower change for the older beams. The lean concretes attain their strength more slowly. Attention is called to the results of Beams No. 336.3, 361.2 and 363.1 in Table 9. These results indicate little or no gain beyond that attained in the ordinary test period.

23. *Relation to Strength of Auxiliary Test Pieces.*—In building construction some auxiliary test may be used with advantage to check up the quality of the concrete placed in beams in which diagonal tension is the critical stress. The writer has suggested the form of flexure test piece here called the "control beam" for this purpose. The modulus of rupture determined from the test of the plain concrete control beam is representative of the tensile strength of the concrete and may be used as its measure, although it does not give the actual tensile strength of the concrete. The resistance of the beam to diagonal tension is dependent upon the tensile strength of the concrete. If the ratio which may be

TABLE 10

VERTICAL SHEARING STRESS, MODULUS OF RUPTURE, AND COMPRESSIVE STRENGTH.

The ratios given are the ratios of the vertical shearing stress to the modulus of rupture of control beams in one case, and to compressive strength of 6 in. cubes in the other. Beams have various percentages of reinforcement. Except as otherwise noted, the age of all beams, control beams and cubes was approximately 60 days. The exact age and amount of reinforcement are given in Tables 6, 8 and 9.

No. of Beam	Year	Kind of Concrete	Vertical Shearing Stress lb. per sq. in.	Control Beam Modulus of Rupture lb. per sq. in.	Ratio	Crushing Strength of 6-in. Cubes lb. per sq. in.	Ratio
210.1	1908	1-1-2	190	492	.39	3960	.048
210.3	"	"	182	390	.47	3570	.051
					Av. .43		.050
211.3	1907	1-1½-3	144	354	.41		
211.1*	"	"	222	331	.67	4590	.048
211.2	"	"	142	310	.46		
211.4	1908	"	142	395	.36	3320	.043
211.5	"	"	181	448	.40		
					Av. .46		.046
212.7	1907	1-2-4	138	336	.41		
212.1	"	"	155	228	.68		
212.2	"	"	162	305	.53		
212.5*	"	"	121	221	.55	3290	.037
212.6	"	"	132	246	.54		
613.2*	"	"	144	280	.51		
616.2*	"	"	190	260	.73		
251.1	"	"	149	291	.51		
251.2	"	"	114	183	.62		
251.3	"	"	102	238	.43		
251.4	"	"	110	288	.38		
417.5	"	"	100	229	.44		
417.6*	"	"	89	189	.47	2420	.037
611.1	"	"	149	293	.51		
611.2	"	"	175	252	.69		
612.1	"	"	153	339	.45		
613.1	"	"	111	307	.36		
616.1	"	"	156	249	.63		
617.1	"	"	169	304	.56		
617.2	"	"	173	304	.57		
217.2	1908	"	152	301	.51	2170	.070
217.4*	"	"	187	439	.43	2910	.064
218.1	"	"	188	333	.56		
218.2	"	"	175	422	.41	2670	.066
218.3	"	"	128	445	.29	2520	.051
218.4	"	"	133			1855	.072
254.1	"	"	132			2100	.063
252.6	"	"	161	452	.36	2330	.069
252.7	"	"	182			3055	.060
253.5	"	"	147	365	.41	3660	.040

* For the age of these tests see Tables 6, 8 and 9.

TABLE 10.—*Continued.*

No. of Beam	Year	Kind of Concrete	Vertical Shearing Stress lb. per sq. in.	Control Beams Modulus of Rupture lb. per sq. in.	Ratio	Crushing Strength of 6-in. Cubes lb. per sq. in.	Ratio
253.6	1908	1–2–4	188			3060	.061
219.1	"	"	193	333	.58		
219.2	"	"	169	422	.40	2670	.063
240.2	"	"	161	321	.50	1780	.090
255.1	"	"	151	492	.31	2230	.068
255.2	"	"	162			2460	.066
220.5	"	"	155	243	.64	2210	.070
220.2	"	"	214	427	.50	2330	.092
256.1	"	"	150	492	.31	2230	.067
256.2	"	"	172	281	.61	2460	.070
253.1	"	"	174			2330	.075
					Av. .50		.064
213.1	1907	1–3–6	98	178	.55		
213.2	"	"	90	204	.44		
213.3	1908	"	170	281	.61	1690	.101
213.4	"	"	104	197	.53	1120	.093
					Av. .53		.097
214.1*	1907	1–4–8	90	179	.50	1315	.068
214.2	"	"	77	174	.44		
415.1	"	"	75	135	.56		
415.2	"	"	64	188	.34		
415.5	"	"	62	151	.41		
415.6	"	"	70	125	.56		
214.3	1908	"	113	183	.62		
214.4	"	"	103	140	.74	1305	.079
352.1	"	"	78	224	.35	1570	.050
352.2	"	"	65			1010	.064
353.2	"	"	70	160	.44	820	.085
					Av. .50		.069
215.1	1907	1–5–10	84	174	.48		
416.5	"	"	49	109	.45		
416.6	"	"	54	118	.46		
215.3*	1908	"	80	132	.61	1100	.073
215.4	"	"	82	176	.47	1175	.070
215.5	"	"	74	176	.42	900	.082
361.1	"	"	62	173	.36	1025	.060
362.1	"	"	61			870	.070
362.2	"	"	43	88	.49	900	.048
363.2	"	"	37	94	.39	600	.062
					Av. .46		.066

* For the age of these tests see Tables 6, 8 and 9.

expected between the vertical shearing strength of the reinforced concrete beam and the modulus of rupture of the control beam be established, this ratio and the flexural strength of the control beam may be used as a measure of the quality of the concrete to resist web stresses. It will be seen that this ratio may vary with different proportional dimensions of beams and with different amounts of cement, but if the ratios be determined for the various conditions, this method should be helpful as an aid to securing substantial construction.

Table 10 gives the ratios of the vertical shearing unit-stress of the reinforced concrete beams to the modulus of rupture of the control beam for the test beams for which control beams were made in those cases where the age of both test beam and control beam was 60 days or thereabouts, and for a few other cases. As only one control beam was made for each test beam, it may be expected that there will be considerable variation in the results. The average of the ratios is about 0.50.

The values of the modulus of rupture of the control beams may be helpful, in connection with other tests, in determining what values should be specified to secure a desired grade of concrete.

The ratio of the vertical shearing unit-stress to the compressive strength given by the cube tests is also given in Table 10 for the cases where the conditions of test are comparable. The ratios are fairly uniform. The usefulness of making field test pieces for tests such as the flexure test and the compression test of cubes or cylinders is a subject worthy of consideration by constructors.

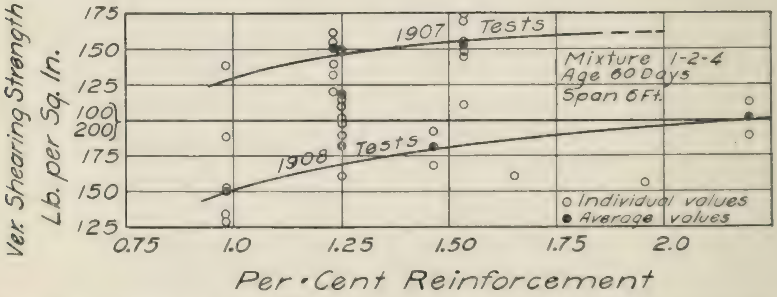

FIG. 10. DIAGRAM SHOWING EFFECT OF AMOUNT OF REINFORCEMENT UPON WEB RESISTANCE

24. *Effect of Amount of Reinforcement.*—Fig. 10 gives values of vertical shearing stress developed with the several percentages of reinforcement used. These beams were all of 6 ft. span and 1–2–4 concrete and were tested at about 60 days' age and all failed by diagonal tension. It is evident that the shearing stress developed in these tests is greater for beams with the larger reinforcement. It is possible that this change is due to the greater deformation (or greater curvature in the elastic curve) of the beams having light reinforcement. Possibly the fact that at the same load tension cracks will be present in the concrete, at points nearer the supports in the beam with the lighter reinforcement on account of the higher tensile stresses developed in the reinforcing steel, has a bearing upon the difference in web resistance. That the bond stresses developed are not the occasion of the variation may be judged from the fact that the beams reinforced with deformed bars carried no higher loads than those with plain round rods.

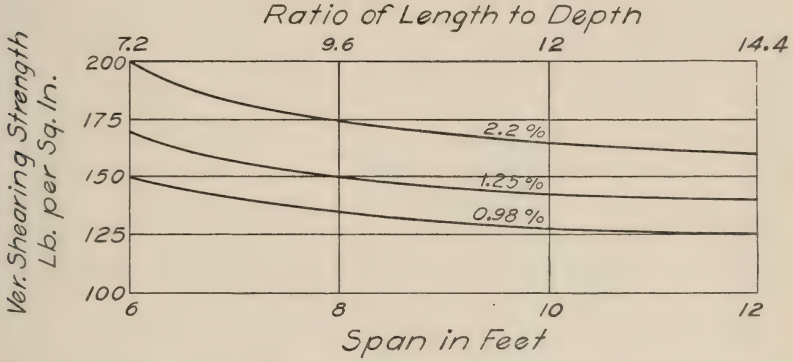

FIG. 11. EFFECT OF SLENDERNESS OF BEAM UPON WEB RESISTANCE.

Fig. 10 has been used for the purpose of reducing the values of shear found in the various tests to the basis of 1 % reinforcement, the amount of the stress being platted at the proper point and then carried to the 1 % line by keeping proportionally distant from the curves shown in the figure. This enables further comparisons to be made.

25. *Effect of Ratio of Length of Span to Depth of Beam.*—In Fig. 11 have been platted values of web resistance for three percentages of reinforcement and for four spans and length ratios, which are thought to be representative of the results of the tests for

1908. These have been selected from average values and reduced to a common basis by the use of the other diagrams. The effect of slenderness of beam, as well as of amount of reinforcement, is brought out in this diagram. The figure has been used in reducing other results to a common basis, in a manner similar to that described in the preceding paragraph.

26. *Appearance of First Diagonal Crack.*—The applied load at which the appearance of a diagonal crack was noted is given in Table 9. In some of the tests no special care was taken to observe the cracks and this may account for part of the variability shown. In the younger and leaner concretes the crack was noted but little before the maximum was reached, and frequently not until failure occured. In the richer and stronger concretes more warning generally was given, and in some beams which carried high loads the diagonal crack was visible for some time before failure.

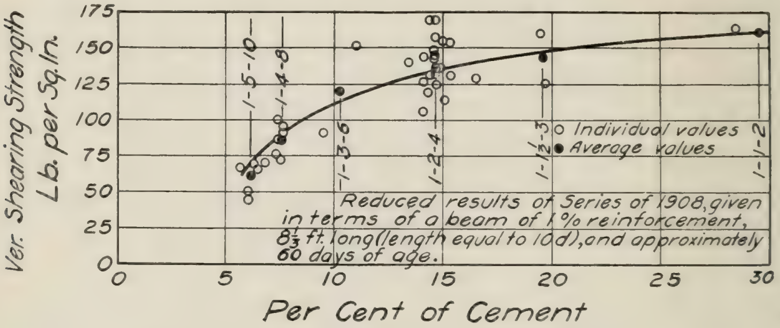

FIG. 12. VALUES FOR WEB RESISTANCE.

27. *Value of Vertical Shearing Stress.*—In Fig. 12 are platted results of tests for 1908—all reduced to a basis of 1% reinforcement and 8⅓-ft. span length (10d) by the use of Fig. 11, as previously described. It is seen that there is a great variation in the results, and this may be expected in a material like concrete. In the selection of working stresses, allowance for the possibility of such variations in reinforced concrete construction should be made.

The marked effect of the addition of cement is of interest, and it is evident that an effective way to provide higher web resistance is to increase the richness of the concrete. Attention is also called to the very low strengths found in the 1906 tests, reported in Bulletin No. 14.

Diagonal tension weakness in reinforced concrete construction should be guarded against. In failures by tension in steel or by compression in concrete warning may be expected through abnormal deflections, but in beams without web reinforcement diagonal tension failures occur suddenly and generally without warning. It seems important, therefore, that relatively low working stresses in shear be used or that effective web reinforcement be provided, and that special care be taken in the construction of parts having high shearing stresses.

B. BEAMS WITH REINFORCING BARS BENT UP.

28. *Beams with Reinforcing Bars Bent up*—The beams of this series were of 1–2–4 concrete and 6-ft. span length. The variations included (see Fig. 13, 14, and 15) (a) bars bent up to a point 2½ in. below the top of the beam at the end, (b) bars bent up to 5 in. below the top, (c) bars bent up to 2½ in. below the top and nuts and washers attached at the end of the bars, (d) bars bent up to 5 in. below the top and nuts and washers attached, and (e) part of the bars bent up and part of them straight. There will also be included in this class the beams made with the Cummings' unit frame. This form of reinforcement is described on page 26. Table 11, page 56, and Table 12, page 57, give data of beams and tests.

29. *Phenomena of Tests of Beams with the Reinforcing Bars Bent Up.*—As may be expected, in the beams with all the bars bent up, as soon as the concrete at the bottom was sufficiently stretched, a vertical tension crack formed at some point between the beam support and the bend of the bar, extending from the bottom of the beam to the level of the reinforcing bars, (see Fig. 13, 14, and 15). After the formation of this vertical crack, the tension in this part of the beam is taken mainly by the reinforcing bar; and as its depth below the top of the beam (and therefore the moment arm of the resisting forces) is considerably less than in beams having the bars horizontal throughout, the tensile stress developed in the bar at this section is greater than in beams having the reinforcement horizontal throughout. The vertical shearing unit-stress actually developed is also greater than in beams having the bars horizontal, and the resulting diagonal tensile stress is therefore greater. As the tensile stress in the steel at

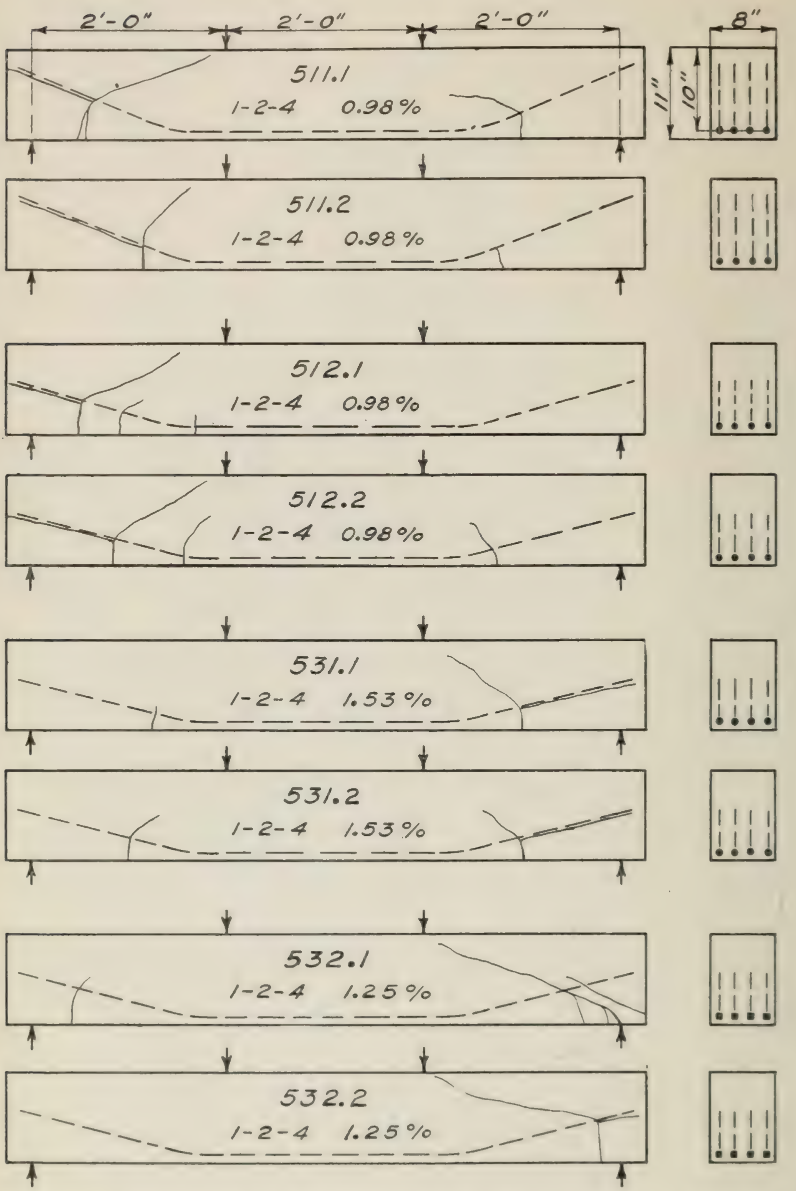

FIG. 13. DISPOSITION OF REINFORCEMENT AND POSITION OF CRACKS.

this section is greater than when the bars are horizontal, the amount of bond brought into action toward the end of the bar must be greatly increased. There is evidently, then, a greater chance for slip of bar in such beams than in beams where straight reinforcement is used. The formation of the vertical cracks gives a good starting point for diagonal tension cracks, and the uneven distribution of stresses in the concrete due to this crack makes diagonal tension failures occur at a lower load than would otherwise be the case. Generally, in these tests, in the beams which did not fail by tension in the steel, the failure came through diagonal tension. The inclined crack which opened up along the line of the bent-up bars, as the concrete below gradually split off, may be said to be the occasion of final failure, though the failure was essentially by diagonal tension. Whether slip occurred after this crack extended along the bars nearly to their ends is a matter of some interest.

The action of the beams having nuts and washers and of beams with part of the bars straight will be seen to be somewhat different from the foregoing.

The following are brief notes of the tests. The location of the cracks is shown in Fig. 13, 14, and 15. The heavy lines indicate cracks along which failure took place. Reference may be made to Tables 11 and 12.

No. 511.1. At 13 000 lb. the first noticeable crack appeared at 2 ft. to right of center and extended from the bottom vertically 3 in. to the level of the reinforcement and then diagonally toward the load point 5 in. At 14 000 lb. a vertical crack appeared 2 ft. 5 in. to left of center and extended to the reinforcing bars. From this point it finally ran diagonally almost to the load point. The beam failed at 18 000 lb., the crack following the reinforcing bars to the end of the beam. The load then dropped quickly to 6000 lb. where it remained constant for some time.

No. 511.2. At 13 000 lb. a crack appeared 1 ft. 10 in. to left of center and extended to the reinforcing bars. At 15 000 lb. this crack had extended diagonally almost to the top of the beam, 4 in. to the left of the load point. The load of 15 000 lb. was held for 15 minutes, due to a break in the machine. The beam failed at 20 000 lb., the load then dropped slowly to 4000 lb., and the crack on the left extended along the reinforcement almost to the end of the beam. An examination of the beam made afterward showed that the bars had slipped $\frac{1}{4}$ in. in the left end.

No. 512.1. At 15 000 lb. two cracks were noted, one 2 ft. 5 in. to the right and the other 2 ft. 1 in. to the left of center, extending upward to the reinforcing bars. At 18 000 lb. a crack appeared 2 ft. 6 in. to the left of center and extended to the reinforcing bars, branching off diagonally to the right toward the load point and to the left along the reinforcing bars. The maximum load was 19 000 lb. and the load gradually dropped to 2000 lb. An examination of the beam showed that the rods at the left end had slipped slightly. The crack had followed the reinforcing bars to the end.

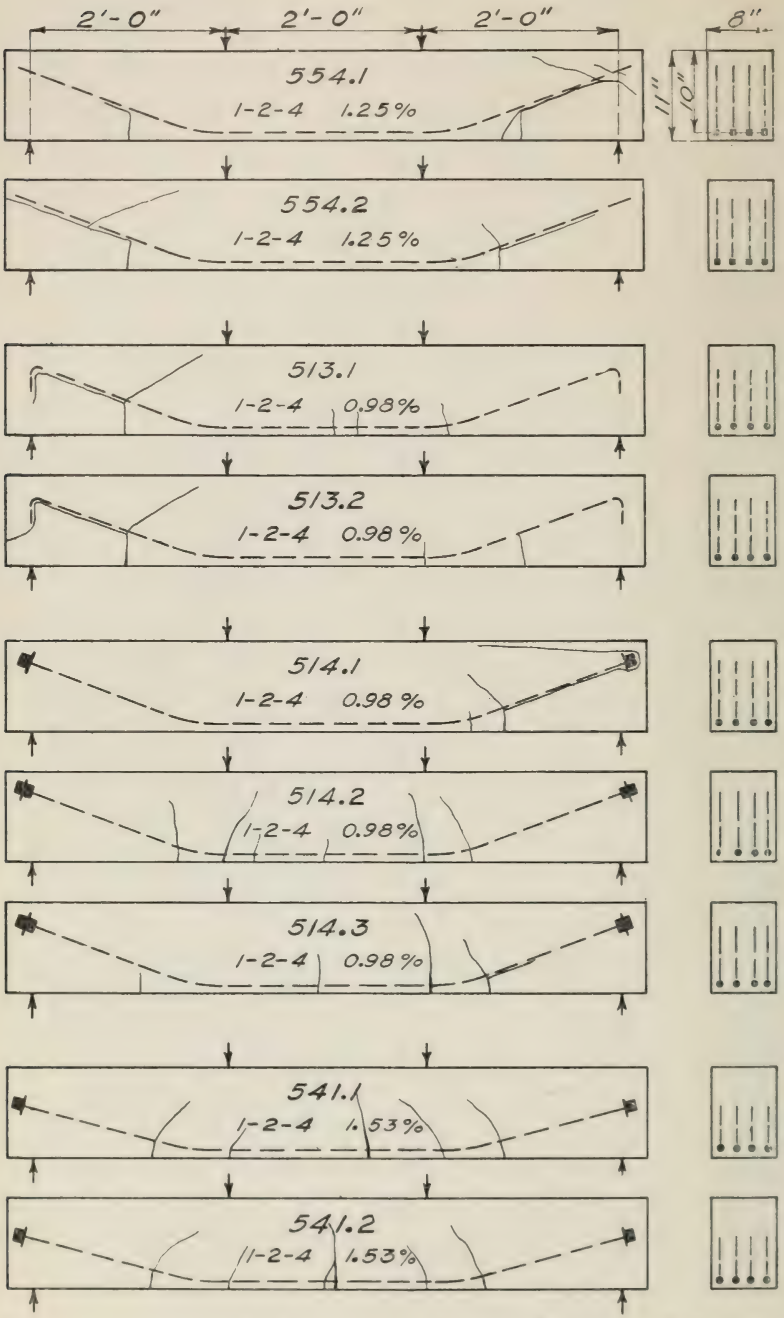

FIG. 14. DISPOSITION OF REINFORCEMENT AND POSITION OF CRACKS.

No. 512.2. At 14 000 lb. a crack appeared 1 ft. 5 in. to left of center and extended toward the load point. At 16 000 lb. a crack was observed 2 ft. 2 in. to left of center, which extended vertically to the reinforcing bars and from here started toward the load point. The beam failed quite suddenly at a load of 17 350 lb., and the crack followed the reinforcing bars to the end of the beam. An examination of the beam showed that the bars had slipped ⅛ in.

No. 531.1. This beam failed in a manner similar to No. 512.1 and at a load but 500 lb. greater. The crack at 1 ft. 10 in. to right of center appeared at 14 000 lb. and the beam failed at 19 500 lb., the crack following the reinforcing bars to the end of the beam.

No. 531.2. At 12 000 lb. a crack appeared 2 ft. to left of center and extended vertically to the reinforcing bars. At 18 000 lb. this crack was 5 in. above the bottom and was extending toward the left load point. At 14 000 lb. a similar crack appeared 2 ft. to right of center and extended in the same way. At 22 000 lb. a slight hair crack was noted following the line of the reinforcement. The beam failed by the opening of the crack at 24 000 lb.

No. 532.1. At 18 000 lb. a diagonal crack appeared at 2 ft. 5 in. to right of center and the beam finally failed along this crack. The maximum load was 20 000 lb.

No. 532.2. At the maximum load of 18 000 lb. a diagonal crack extended from the right end toward the load point. The bars slipped after the diagonal tension failure occurred.

No. 554.1. At 13 600 lb. a vertical crack appeared 1 ft. 10 in. to left of center and one 2 ft. to the right of center which extended 4 in. high to another crack. At 17 900 lb. the beam failed as shown in the sketch in Fig. 14.

No. 554.2. At 10 800 lb. a vertical crack appeared 2 ft. to the left of center, extending up to the reinforcement, thence along the reinforcement to the end of the beam. A similar crack appeared 1 ft. 9 in. to the right of center. At a maximum load of 17 500 lb. the beam failed along the crack to the left of center.

No. 513.1. At 9 000 lb. a crack appeared 2 ft. to left of center and extended vertically to the reinforcing bars. The beam failed suddenly at 16 700 lb. The crack followed the reinforcement to its end.

No. 513.2. At 10 000 lb. a crack appeared 2 ft. to left of center, extending vertically to the reinforcing bars. As the load increased this crack extended diagonally toward the load point. The beam failed at 16 400 lb.; this crack following the reinforcing bars to the end.

No. 514.1. At 10 000 lb. a crack appeared at 1 ft. 10 in. to right of center and extended to the reinforcement. The beam failed suddenly at 21 100 lb. by this crack running along the reinforcement to the nuts. At failure a crack appeared at the nut, running back toward the load point. The diagonal crack shown closed up. This is a peculiar failure and differs from others of its set. As noted elsewhere the washers were not locked to the end nuts in this beam.

No. 514.2. This beam is noteworthy because it failed through tension in the steel, although a crack was visible along the reinforcing bars. At 14 000 lb. a crack appeared to the right of the right load point and finally extended some distance toward the load point. At 19 000 lb. slight cracks were seen following the reinforcement from this crack. At 16 000 lb. a vertical crack 3 in. long appeared at the center and also a crack below the left load point which extended upward 4 in. At the maximum load of 22 200 lb. this crack was 8 in. high, and opening considerably, showing failure by tension in the steel. At 18 000 lb. a vertical crack 6 in. long was noted 1 ft. 6 in. to left of center and at the maximum load it was 8 in. long. The deflection of the beam at the maximum load was 0.2 in. and the load remained within 1000 lb. of the maximum until the deflection was 0.43 in. Crushing of the concrete at the top of the beam occurred under the increased deflection.

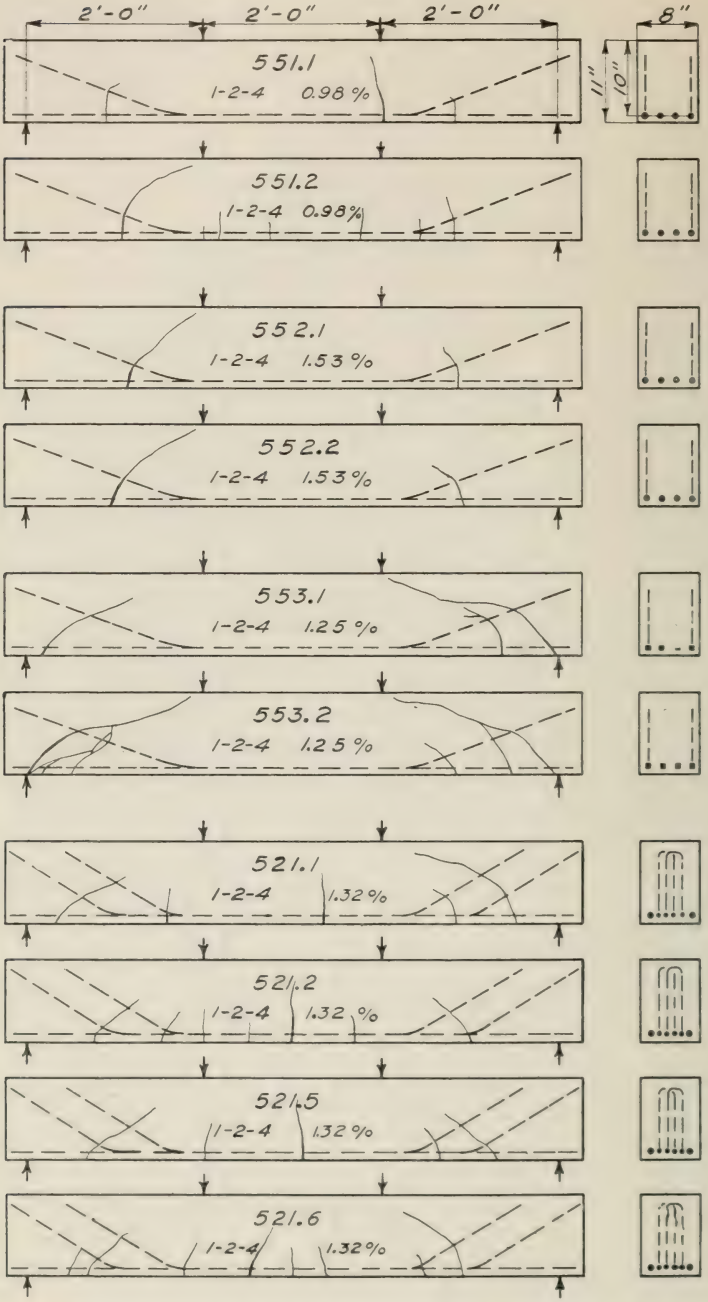

FIG. 15. DISPOSITION OF REINFORCEMENT AND POSITION OF CRACKS.

No. 514.3. At 12 000 lb. a crack appeared 1 ft. 8 in. to right of center and extended vertically 4 in. At 18 000 lb. a crack had branched off from the first crack and followed the reinforcement for a short distance. At 22 000 lb. a crack appeared under the right load. At the maximum load of 23 500 lb. this crack was 8 in. high and as the deflection of the beam was increased the crack opened up almost to the top of the beam and finally the concrete began to crush at the top. The beam failed by tension in the steel. The effect of the anchorage is shown in that the inclined crack did not extend to the end of the bar.

No. 541.1. At 16 000 lb. the first crack appeared at 1 ft. 10 in. to left of center and was 2½ in. long. At 18 000 lb. it had extended toward the load point until it was 5 in. from the bottom of the beam and at 28 000 lb. it was 7 in. A similar crack appeared at 1 ft. 10 in. to right of center at 18 000 lb. and at 26 000 lb. this crack was visible 7 in. above the bottom of the beam. At 18 000 lb. cracks were noted under the two load points. At 22 000 lb. a crack 5 in. to right of center was 2 in. high. At the maximum load of 29 600 lb. this crack was 6 in. long. This load was held almost constant for some time and the beam failed by tension in the steel, followed by crushing of the concrete at the top of the beam.

No. 541.2. This beam failed in a manner similar to No. 541.1. At 12 000 lb. the first crack appeared 1 ft. 7 in. to right of center and extended 4 in. toward the load point. At 14 000 lb. a similar crack appeared 1 ft. 10 in. to left of center. At 16 000 lb. this crack was 8 in. above the bottom of the beam. At 16 000 lb. a small vertical crack was observed near the center. The maximum load was 28 450 lb. The beam failed by tension in the steel.

No. 551.1. At 14 000 lb. a crack appeared 1 ft. 10 in. to right of center, extending vertically 3 in. At 16 000 lb. a similar crack appeared 2 ft. 1 in. to left of center. At 22 000 lb. a slight vertical crack was noted under the right load point. This gradually extended upward until the maximum load of 24 700 lb. was reached. The beam failed by tension in the steel and an examination showed that the rods had scaled. The cracks in the other one-third did not develop to any extent.

No. 551.2. At 14 000 lb. two cracks appeared; one 2 in. long at the right one-third point and one 4 in. long near the left one-third point. At 16 000 lb. a vertical crack 6 in. long was noted 1 ft. 11 in. to left of center. At 18 000 lb. three more vertical cracks were noted in the middle third. The beam failed at a load of 22 000 lb. by the crack in the left third of the beam extending to the load point and at the same time following the line of horizontal reinforcement. This diagonal tension failure was at a load which nearly developed the elastic limit of the steel.

No. 552.1. At 22 000 lb. a crack appeared 10 in. to left of left load point 5 in. high and at 23 000 lb. one 14 in. to right of right load point 4 in. high. Failure at 25 000 lb. by the extension of the first crack to the load point.

No. 552.2. At 24 000 lb. a crack appeared 10 in. to right of right load point 5 in. high, and at 25 000 lb. one 17 in. to right of right load point 5 in. high. At 28 000 lb. these cracks were opening and lengthening. At 30 000 lb. the cracks were extended well toward the load point. Final failure came at the left end, the crack reaching from support to load point.

No. 553.1. At 24 000 lb. a diagonal crack appeared 2 ft. 4 in. to right of center and at 24 700 lb. one at 2 ft. 10 in. to left of center. These cracks gradually lengthened and at 28 800 lb. the beam failed by diagonal tension. It will be noted that the failure crack extended to the support.

No. 553.2. At 24 000 lb. a diagonal crack appeared 1 ft. 10 in. to right of center, at 25 000 lb. another at 2 ft. 5 in. to right of center, and at 26 000 lb. one at 2 ft. 6 in. to left of center. These cracks gradually opened and lengthened and at 31 000 lb. the maximum load was reached. The crack at the right end extended almost to the load point, and the final failure came at the crack at the left end which reached from support to load point.

No. 521.1. This is the Cummings' unit frame reinforcement. It should be noted that the cracks outside the load points were small and did not extend far, and that failure was by tension in the steel at a high vertical shearing stress. At 20 000 lb. the first crack appeared at 4 in. to right of center and extended upward 4 in. At 22 000 lb. a crack appeared 2 ft. 6 in. to right of center, extending upward 6 in. Another crack 4 in. long was noted 1 ft. 5 in. to the left of center, inclined toward the load point. At 28 000 lb. slight vertical cracks were noted 1 ft. 10 in. to right of center and 2 ft. 8 in. to left of center. The beam failed by tension in the steel at the crack near the center, the maximum load being 31 100 lb. The load ran near the maximum for some time as the deflection was increased and finally the concrete crushed slowly at the top.

No. 521.2. Another Cummings' reinforcement. The first noticeable crack was at the center of the beam at 16 000 lb., extending upward 3 in. At 18 000 lb. a slight crack appeared at the left one-third point. At 20 000 lb. two cracks appeared both inclined toward the load points, one 2 ft. 3 in. to left of center and the other 2 ft. to right of center. At 22 000 lb. a vertical crack appeared at 8 in. to right of center and at 24 000 lb. at 6 in. to left. At 26 000 lb. a crack 6 in. long appeared 1 ft. 6 in. to left of center and inclined toward the load point. At the maximum load of 35 000 lb. the crack at the center had gradually extended, opening up, and the beam failed by tension in the steel. The load remained near the maximum under further deflection and crushing of the concrete at the top of the beam finally occured. The beam held 34 000 lb. until a deflection of nearly 0.5 in. had been reached. The outer cracks had not developed particularly and there was no appearance of cracks in the direction of the reinforcement.

No. 521.5. Another Cummings' reinforcement. At 20 000 lb. a crack appeared 2 ft. 3 in. to right of center, inclined slightly toward the left. At 24 000 lb. slight vertical cracks were noted at the left one-third point. At 26 000 lb. a crack appeared 2 ft. 4 in. to left of center and inclined toward the load point. At this load a vertical crack 2 in. long was observed 1½ in. to right of center. At 32 500 lb. this crack had opened almost to the top of the beam and the beam failed by tension in the steel. The load carried dropped and crushing of the concrete finally occurred.

No. 521.6. Another Cummings' reinforcement. At 16 000 lb. an inclined crack 6 in. long was visible 2 ft. 4 in. to left of center. At 18 000 lb. an inclined crack 1 ft. 11 in. to right of center appeared which at 26 000 lb. had extended 8 in. from the bottom of the beam. It finally reached almost to the load point. At 18 000 lb. a vertical crack 2 in. long appeared 6 in. to left of center. At 20 000 lb. a vertical crack 2 in. long was noted at the center of the beam. The beam carried a maximum load of 26 200 lb. The deflection diagram is somewhat different from the other beams. The method of failure was evidently by tension in the steel aided by a yielding of the concrete which decreased the moment arm. The stress in the steel is therefore greater than the calculations make it. There was evidence that the concrete in this beam was not so good as in the other beams.

30. *Web Resistance with All Bars Bent Up.*—It seems to make little difference in results, either as to the load carried or as to the manner of failure, whether the bars were bent up to a point close to the top of the beam or to a point 5 in. below the top. For No. 511.1 and 511.2 the value of the nominal vertical shearing stress developed was 145 lb. per sq. in. and for No. 512.1 and 512.2, 140

lb. per sq. in. In both sets vertical cracks (see Fig. 13, 14, and 15) appeared in the outer thirds of the span length, running up to the reinforcing bars. These cracks formed at a nominal vertical shearing stress averaging 105 lb. per sq. in. in No. 511.1 and 511.2, and 112 lb. per sq. in. in No. 512.1 and 512.2. These cracks generally appeared at points about 7 in. from the supports, though in one beam the crack which caused failure was 14 in. from the support. The diagonal crack extended well to the load point before the maximum load was reached. Under these conditions the inclined crack along the reinforcing bars extended and opened, due mostly to the stiffness of the lower segment of the beam next to the support which had no stresses tending to bend it. At final failure there was a slip of the bars at their ends, although the diagonal crack was the real cause of failure. The opening or extension of the inclined cracks helped to concentrate the bond stresses near the end of the bar until these stresses must have become very large. The result of No. 513.1 and 513.2, in which the bars were hooked downward at their ends, indicates that the bars were peeled off, so to speak, although in this case the tension in the rod would have to be carried around its end through the concrete. In passing, it may be noted that it had been planned to hook these bars upward but the workmen made the bend downward.

No. 531.1 and 531.2, which had a higher percentage of reinforcement and therefore had developed less stretch in the steel and less bond stress at a given load and less deflection, gave results higher than 512.1 and 512.2, say 20 per cent more, though the method of failure was the same. The amount of bond surface available was 20 per cent greater. No. 532.1 and 532.2, which were reinforced with corrugated bars, developed a value of the nominal vertical shearing stress of 150 lb. per sq. in.; No. 554.1 and 554.2 gave lower results, 138 lb. per sq. in. As the bond surface available in these four beams was about the same as in No. 531.1 and 531.2 and as the deformed bar would have much greater bond resistance, it would seem that the failure of the beams with bars bent up was not due primarily to slip of bars. A more probable occasion of failure is the splitting of the concrete along the line of the inclined bars after the diagonal cracks have formed by reason of the lack of flexural action in the concrete below the inclined

TABLE 11.

DATA OF BEAMS WITH REINFORCING BARS BENT UP.

Series of 1907.

Span length 6 feet.

Beam No.	Kind of Concrete	Cement		Longitudinal Reinforcement		
		Kind	Per cent	Description	Per cent	Disposition
511.1	1-2-4	AA	16.7	4 ½-in. round	0.98	Bent to 2½ in. of top
511.2	do.	AA	16.5	do.	0.98	do.
512.1	do.	AA	16.3	do.	0.98	Bent to 5 in. of top
512.2	do.	AA	15.7	do.	0.98	do.
531.1	do.	AA	15.7	4 ⅝-in. round	1.53	do.
531.2	do.	AA	15.5	do.	1.53	do.
532.1	do.	AA	14.6	4 ½-in. cor. h. s.	1.25	do.
532.2	do.	AA	14.3	do.	1.25	do.
554.1	do.	AA	17.5	do.	1.25	Bent to 2½ in. of top
554.2	do.	AA	14.3	do.	1.25	do.
513.1	do.	AA	15.1	4 ½-in. round	0.98	Bent to 2½ in. of top and hooked downward at ends
513.2	do.	AA	15.6	do.	0.98	
514.1	do.	AA	16.0	do.	0.98	Bent to 2½ in. of top, with nuts and washers
514.2	do.	AA	15.8	do.	0.98	
514.3	do.	AA	15.5	do.	0.98	do.
541.1	do.	AA	15.9	4 ⅝-in. round	1.53	Bent to 5 in. of top, with nuts and washers
541.2	do.	AA	16.0	do.	1.53	
551.1	do.	AA	15.6	4 ½-in. round	0.98	Two bars to 2½ in. of top, two bars straight
551.2	do.	AA	15.5	do.	0.98	
552.1	do.	AA	15.1	4 ⅝-in. round	1.53	do.
552.2	do.	AA	15.9	do.	1.53	do.
553.1	do.	AA	15.9	4 ½-in. cor. h. s.	1.25	do.
553.2	do.	AA	15.1	do.	1.25	do.
521.1	do.	AA	15.8	Cummings' welded loops, 2 ⅝-in. and 4 ⅜-in. round	1.32	Bent up at two points and fastened to cross ties
521.2	do.	AA	15.9		1.32	
521.5	do.	U	15.2		1.32	
521.6	do.	U	16.1		1.32	

part of the bars. Beams with the heavier reinforcement would have less deflection for the same load and as this gives a flatter elastic curve the tendency for the inclined crack to form would be less.

TABLE 12.

TESTS OF BEAMS WITH REINFORCING BARS BENT UP.

Series of 1907.

All beams failed by diagonal tension unless otherwise noted.

Beam No.	Age days	Load at First Diagonal Crack pounds	Maximum Applied Load pounds	Stress in Longitudinal Reinforcement lb. per sq. in.	Nominal Vertical Shearing Stress lb. per sq. in.	Nominal Bond Stress lb. per sq. in.	Control Beam	
							Modulus of Rupture lb. per sq. in.	Age days
511.1	70	13 000	18 000	33 100	138	186	231	60
511.2	65	13 000	20 000	36 800	153	207	363	64
512.1	70	15 000	19 000	55 000	146	197	241	60
512.2	63	14 000	17 400	32 100	134	181	275	62
531.1	63	14 000	19 500	23 500	153	156	207	62
531.2	62	12 000	24 000	28 900	187	191	346	63
532.1	62	18 000	20 600	30 000	159	159	291	63
532.2	61	18 000	18 000	26 300	140	140	288	61
554.1	61	......	17 900	26 200	139	139		
554.2	61	......	17 500	25 600	136	136	238	61
513.1	70	......	16 700	30 800	129	174	239	60
513.2	62	10 000	16 400	30 300	127	172	284	63
514.1	65	10 000	21 100	38 700	161	218	207	64
514.2*	62	14 000	22 200	40 700	169	228	253	62
514.3*	63	......	23 500	43 000	179	242	346	63
541.1*	61	16 000	29 600	35 400	229	234	245	60
541.2*	62	12 000	28 450	34 200	220	224	304	61
551.1*	63	14 000	24 700	45 200	188	254	284	63
551.2	67	14 000	22 000	40 400	168	227	294	60
552.1	59	22 000	25 000	30 100	194	198	352	59
552.2	59	20 000	29 200	35 000	226	230	266	60
553.1	59	24 000	28 800	41 700	220	220	266	60
553.2	59	24 000	31 000	45 000	240	240	352	59
521.1*	63	22 000	31 100	42 800	238	...	213	62
521.2*	67	20 000	35 000	48 200	266	...	245	60
521.5*	61	20 000	32 500	44 800	248	...	313	60
521.6*	62	16 000	26 200	36 200	201	...	231	61

* Tension failure.

The values for the nominal vertical shearing stress in the beams under consideration do not differ much from the vertical shearing stresses developed in the beams of the 1907 series having reinforcing bars horizontal, and hence no gain in resistance was obtained by bending up the bars in this way. Of course, if calculations be made on the basis of the distance of the bars from the top of the beam at the point where the diagonal crack started, the stress so calculated will be two or three times as great. For the same reason the bond stress near the end of the bars will be much higher than the nominal bond stress given in the tables. There is, therefore, a high tendency to slip, particularly after the inclined cracks have opened some distance. There is an advantage over the construction with the bars straight in that failure of the beams was less sudden and there was more warning.

Attention is called to the low strengths found in beams with poor concrete in the 1906 tests (Bulletin No. 14, page 27).

31. *Web Resistance with Anchored Bars.*—Of the beams having the reinforcing bars anchored with nuts and washers, No. 514.1 failed suddenly at a nominal vertical shearing stress of 161 lb. per sq. in., but the segment at the support split off as shown in Fig. 14, and the small diagonal crack which had formed closed up. It should be noted that in this beam the washers were not fastened against the nuts and there was chance for slip before the washers had solid anchorage. As the other two beams of this set contained a second nut which locked the washer in position, it is possible that this difference in construction explains the lower value and the failure of No. 514.1. In No. 514.2 and 514.3 an inclined crack following the bars for a short distance was visible at one end of the beam for some time before failure, but the manner of failure was by tension in the steel. Beams No. 541.1 and 541.2, having 1.53 % reinforcement and nuts and washers at the ends, also failed by tension of the steel, developing the high nominal vertical shearing stresses of 229 and 220 lb. per sq.in. The diagonal cracks which had formed were closer to the load points than were those in beams having the bars anchored. The general distribution and direction of the cracks are quite different from those of the other beams, and it appears that considerable arch action must have developed. It seems evident from these tests that anchorage of bars at the ends, in beams with bars bent up, if securely arranged, may be advantageous in increasing web resistance. It is true, also, that this form of construction is an insurance against failure at low loads through defective concrete or insufficient bond.

32. *Web Resistance with Part of the Bars Bent Up.*—In the beams in which two bars were bent and two were left straight, vertical cracks formed outside the load points at about the same loads as in the other beams. No. 551.1 failed by tension in the steel at a nominal vertical shearing stress of 188 lb. per sq. in. without the diagonal tension cracks extending very far. In No. 551.2 failure by diagonal tension came at a nominal shearing stress of 168 lb. per sq. in., the diagonal cracks extending to the load point and a crack following the line of the horizontal reinforcement. No. 552.1 and 552.2 failed by diagonal tension at an average nominal vertical shearing stress of 210 lb. per sq. in. It will be noted that the bars of these beams have more bond surface available and that the increased amount of reinforcement makes a stiffer beam than No. 551.2. No. 552.1 and 552.2, reinforced with round rods, and No. 553.1 and 553.2, reinforced with corrugated bars, developed high resistance to diagonal tension, the nominal vertical shearing stress averaging 210 and 230 lb. per sq. in., respectively. This is a high web resistance. The position and distribution of the cracks are quite different from those in the preceding beams.

It is seen that beams with part of the bars bent up and part left straight developed higher resistance to diagonal tension than beams with all bars horizontal or beams with all bars bent up. It is evident also that to secure best results in providing against diagonal tension stresses, the diagonal bars should be well distributed through the part of the beam where high web resistance is needed. This may be accomplished, when there are several bars, by bending the bars in two or more lines parallel to each other, as is shown in the Cummings' reinforcement, and as is common practice with the ordinary reinforcement. It may be expected, then, that good results may be obtained by bending up part of the bars if proper care is taken to get a good distribution of the diagonals.

33. *Web Resistance of Cummings' Reinforcement.*—As noted on page 54, all the beams reinforced with the Cummings' system of reinforcement failed by tension in the steel. The nominal vertical shearing stress developed was high, averaging 238 lb. per sq. in.; how much greater stress could have been developed is not known. The cracks in the outer thirds of the span length were

well distributed and opened up very little. The principle on which this form of reinforcement is based seems rational,—the main reinforcement is carried horizontally to the end of the beam, the smaller bars are bent up and this bending is made in two planes (i. e., begins at two points), the bars are brought together at their ends and thus are anchored, and the reinforcement is connected by a cross bar at the points where bending up begins, which aids in distributing the web stresses among the bars. It does not seem that welding the bars at the loop is essential, bending them around with sufficient anchorage may give the same effect, and other devices of similar make-up may be expected to give good results. It may be added that a unit frame has many advantages in reinforced concrete construction, one important feature being to insure that the reinforcement is properly placed and is retained in the proper place during fabrication.

C. BEAMS WITH STIRRUPS.

34. *Beams with Stirrups.*—Tests of 43 beams having stirrups for web reinforcement are included in the 1907 series, and 12 beams in the 1908 series. A classification of the beams according to the longitudinal and the web reinforcement used may be made as follows: (a) longitudinal reinforcement,—(1) smooth round bars, (2) deformed bars; (b) stirrups,—(1) smooth round rods, (2) smooth round rods bent at top, (3) smooth round rods having a reduced section, (4) smooth round rods wrapped with paper for a part of their length, (5) corrugated bars of high elastic limit, (6) corrugated bars of mild steel. In addition to these, test beams were made of 1–5–10 concrete to determine the effect of poor concrete. Other beams were tested to study the effect of unsymmetrical loading. The tests were planned with a view of determining the amount of stress (tension and bond) developed in the stirrups. However, for various reasons, the results are of less value than was expected. The beams were not all made according to the plans. In the 1907 tests, the stirrups in a few of the beams were poorly placed and even left exposed at the face of the beam, and a variation in the temperature conditions of the laboratory also affected the results. It is evident from the results that the stresses developed in the stirrups are less than they were calculated to be, and hence the layout was not well planned to settle the points at issue. The tests, however, give considerable information on the

effectiveness of stirrups in providing web resistance.

Tables 13, p. 62 and 64, and 14, p. 63 and 65, give data of the beams and of the tests. The values of tensile stress in stirrups were obtained by equation (21) as described on page 18. The bond stresses developed were calculated as described on page 20, using as the bond surface the surface area of the stirrup for six-tenths of the distance from the top of the beam to the center of the longitudinal reinforcement.

35. *Phenomena of Tests.*—It seems evident from the tests that the stirrups did not take much stress until after the formation of diagonal cracks. Diagonal cracks appeared on the surface of the beam at loads giving the same vertical shearing stress v as those at which cracks appear in beams of the same span, reinforcement, and quality of concrete not having web reinforcement, or at loads somewhat greater. A good illustration of the way in which deformations begin to show in stirrups is given in Bulletin No. 28, "A Test of Three Large Reinforced Concrete Beams." The diagram of vertical readings (Fig. 10, p. 22) shows first a vertical shortening followed by elongation. The point of beginning of marked elongation is at or near the load at which diagonal cracks appeared in the other beam test. It seems evident that there is very little elongation in stirrups until the first diagonal crack forms, and hence that up to this point the concrete takes practically all the diagonal tension. If, after diagonal cracks have formed, the load is released and then reapplied, the stirrups will take stress from the beginning. This is discussed in Bulletin No. 28 already referred to.

After the cracks become visible, the stirrups take tensile and bond stresses, and the diagonal cracks extend and enlarge. Finally the diagonal cracks enlarge considerably. The inability to carry a greater load was essentially a diagonal tension failure in all cases where failure occurred outside the load points. A feature of the tests of beams with stirrups is slow failure, the load holding well up to the maximum under increased deflection and giving warning of its condition.

Not enough information was obtained to determine the actual final occasion of failure in these tests. In a number of cases the stirrups slipped, in others it seemed that the steel in the stirrups was stretched beyond its elastic limit, and in some cases the

TABLE 13.
Data of Beams with Stirrups.
Series of 1907.

Beam No.	Kind of Concrete	Cement		Longitudinal Reinforcement		Stirrups	
		Kind	Per cent	Description	Per cent	Description	Spacing
231.1	1–2–4	AA	18.3	4 ½-in. cor. bars	1.25	¼-in. cor. h. s.	6
231.5	do.	U	15.8	do.	1.25	do.	6
231.6	do.	U	15.5	do.	1.25	do.	6
232.1	do.	AA	18.3	do.	1.25	¼ in. cor. m. s.	4
232.2	do.	AA	16.3	do.	1.25	do.	4
232.5	do.	U	16.	do.	1.25	do.	4
232.6	do.	U	16.	do.	1.25	do.	4
233.1	do.	AA	18.7	do.	1.25	½-in. cor. m. s.	8
233.2	do.	AA	16.3	do.	1.25	do.	8
233.5	do.	U	16.2	do.	1.25	do.	8
233.6	do.	U	13.9	do.	1.25	½-in. round	8
233.7	do.	U	15.3	do.	1.25	⅝-in. round	8
235.1	1–5–10	AA	6.4	do.	1.25	¼-in. cor. m. s.	4
235.2	do.	AA	7.2	do.	1.25	do.	4
235.5	do.	U	6.3	do.	1.25	do.	4
235.6	do.	U	6.7	do.	1.25	do.	4
241.5	1–2–4	U	16.	do.	1.25	½-in. round bent	8
241.6	do.	U	15.5	do.	1.25	do. [inward	8
242.1	do.	AA	12.6	4 ½-in. round	0.98	½-in. round	8
242.2	do.	AA	14.9	do.	0.98	do.	8
243.1	do.	AA	15.6	4 ½-in.cor.bar h.s.	1.25	do.	8
243.2	do.	AA	12.6	4 ½-in. round	0.98	do.	8
244.1	do.	AA	14.9	do.	0.98	do.	6
244.2	do.	AA	15.6	4 ½-in. cor. bar	1.25	do.	6
271.5	do.	U	15.9	2 1¼-in. angles	1.11	Expanded metal	
271.6	do.	U	15.5	do.	1.11	do.	
221.1	do.	AA	15.8	3 ¾-in. round	1.65	½-in. round	5
221.2	do.	AA	15.7	do.	1.65	do.	5
221.5	do.	U	15.5	do.	1.65	do.	5
221.6	do.	U	15.2	do.	1.65	do.	5
222.5	do.	U	15.4	5 ½-in. round	1.23	⅝-in. round re-	5
222.6	do.	U	15.7	4 ½-in. round	0.98	do. [duced to 5/16	5
223.1	do.	AA	16.0	do.	0.98	¼-in. round m. s.	3
223.5	do.	U	15.6	5 ½-in. round	1.23	do.	3
223.6	do.	U	15.6	do.	1.23	do.	3
224.5	do.	U	15.7	do.	1.23	¼-in. round re-	3
224.6	do.	U	15.7	4 ½-in. round	0.98	do. [duced to 7/32	3
225.5	do.	U	16.6	3 ¾-in. round	1.65	⅝-in. round	7
225.7	do.	U	15.4	4 ½-in. round	0.98	do.	7
226.5	do.	U	15.6	do.	0.98	½-in. round; lower 4	5
226.6	do.	U	15.6	do.	0.98	in. wrapped in paper	5
227.5	do.	U	15.6	3 ¾-in. round	1.65	½-in. round	5
227.6	do.	U	15.6	do.	1.65	do.	5
228.5	do.	AA	15.5	do.	1.65	¼-in. round	3
228.6	do.	U	15.5	do.	1.65	do.	3

[Continued on page 64.

TABLE 14.

TESTS OF BEAMS WITH STIRRUPS.

Series of 1907.

All beams failed by diagonal tension unless otherwise noted.

Beam No.	Age days	Load at First Diagonal Crack pounds	Maximum Applied Load pounds	Stress in Longi'nal Reinforcement lb. per sq.in.	Vertical Shearing Stress lb. per sq. in.	Bond in Longi'nal Rein. lb. per sq. in.	Tensile Stress in Stirrups lb. per sq. in.	Bond in Stirrups lb. per sq. in.
231.1	60	25 260	33 000	47 800	251	251	96 400	1004
231.5	66	18 000	35 800	51 800	272	272	104 400	1088
231.6	71	20 000	31 800	46 000	242	242	93 000	968
232.1*	60	28 000	38 000	55 000	281	281	72 000	750
232.2*	60	24 000	40 300	58 200	306	306	78 400	815
232.5	62	17 000	22 000	32 000	170	170	43 500	453
232.6	61	19 000	25 000	36 300	192	192	49 100	512
233.1*	61	27 000	43 300	62 500	328	328	42 000	874
233.2	61	20 000	34 700	50 200	264	264	33 800	705
233.5	63	14 000	34 000	49 300	259	259	33 100	690
233.6	61	14 000	29 300	42 500	224	224	36 500	714
233.7	63	23 000	27 200	39 500	208	208	21 600	563
235.1	63	14 500	14 500	21 900	116	116	29 800	310
235.2	61	17 000	17 800	26 700	141	141	36 100	376
235.5†	61	6 100	6 100	9 600	52	52	13 300	139
235.6	61	8 000	11 900	18 100	100	100	25 600	267
241.5	59	18 000	32 300	46 700	246	246	40 200	834
241.6	52	18 000	29 400	42 600	224	224	37 500	760
242.1*	60	21 300	22 500	41 300	171	218	27 900	580
242.2*	60	20 000	24 500	44 800	193	246	31 500	580
243.1	60	26 000	44 300	64 000	336	336	34 900	1140
243.2*	60	24 000	26 000	47 600	197	251	32 400	668
244.1*	60	22 000	24 100	43 300	185	185	22 600	470
244.2	60	24 000	28 200	40 800	216	216	26 500	549
271.5	59	12 000	13 800	22 800	110			
271.6	61	15 000	16 300	26 700	127			
221.1	60	17 000	25 000	28 000	195	221	19 900	413
221.2	58	22 000	26 000	29 100	203	230	20 700	430
221.5	60	20 000	23 000	25 800	181	205	18 500	383
221.6	59	21 000	21 000	23 600	165	187	16 800	350
222.5	61	20 000	23 700	35 000	182	185	47 600	310
222.6	20	17 000	17 200	32 500	132	168	34 400	224
223.1	61	16 000	19 000	35 000	146	186	35 800	372
223.5	61	19 000	22 600	33 400	174	177	42 700	443
223.6	63	4 000	21 000	31 100	162	165	39 700	412
224.5	60	14 000	21 800	32 300	168	171	52 200	427
224.6*	60	18 000	21 200	38 900	164	209	51 000	417
225.5	59	22 000	22 000	34 700	173	196	15 800	411
225.7	59	20 000	21 700	39 800	165	210	15 000	392
226.5	60	19 000	20 100	36 900	154	196	15 700	326
226.6	61	16 000	21 000	38 600	160	204	16 300	339
227.5	63	18 000	20 000	22 500	158	179	16 100	335
227.6	60	15 000	16 400	18 500	130	147	13 300	275
228.5	59	16 000	17 500	19 700	138	156	33 800	351
228.6	60	19 000	21 400	24 000	168	190	41 400	428

*Tension failure. †Appearance indicated poor concrete.

[Continued on page 65.

TABLE 13.—*Continued.*

DATA OF BEAMS WITH STIRRUPS.

Series of 1908.

Beam No.	Kind of Concrete	Cement		Longitudinal Reinforcement		Stirrups	
		Kind	Per cent	Description	Per cent	Description	Spacing inches
221.3	1–2–4	AA	15.7	3 ¾-in. round	1.65	½-in. round	5
221.4	do.	AA	16.2	do.	1.65	do.	5
223.2	do.	AA	15.7	5 ½-in. round	1.23	¼-in. round	3
223.3	do.	AA	16.2	do.	1.23	do.	3
229.1	do.	AA	15.3	do.	1.23	½-in. round (one end only)	5
229.2	do.	AA	15.2	do	1.23	do.	5
229.5	do.	AA	14.3	do.	1.23	½-in. cor. m. s. (one end only)	5
229.8	1–1½–3	AA	24.5	do. 2 bent [up	1.23	½-in. cor. h. s. (one end only bars bent up at other end)	5
233.3	do.	AA	15.9	4 ½-in. round	0.98	½-in. round	8
233.4	do.	AA	15.7	4 ½-in. cor.	1.25	½-in. cor. m. s.	8
240.1	do.	AA	15.3	3 ¾-in. round nuts and washers	1.65	½-in. round	5
243.3	do.	AA	15.3	4 ½-in. cor.	1.25	do.	8

stirrups broke; possibly in some the longitudinal reinforcement slipped. In a number of tests the general racking or breaking up of the concrete was the evident cause of failure. The following notes of the tests are given.

Beam No. 231.1 (See Fig. 16). At 25 000 lb. diagonal crack marked (1) was noted 10 in. to left of left load. At 26 000 lb. cracks appeared in middle third and diagonal crack (2) was noted, and at 28 000 lb. diagonal cracks (3) and (4). At 29 000 and 30 000 lb. cracks marked (5) and (6) noted at left end of beam. At 32 000 lb. metallic noises were heard and diagonal cracks continued to open. Maximum load, 33 000 lb. Load dropped to 14 900 lb. as ultimate failure occured at (3) and (4); stirrup marked (a) broke, and stirrup marked (b) slipped.

Beam No. 232.1. At 26 000 lb. vertical crack marked (1) appeared. At 28 000 lb. diagonal crack (2) was noted at left end and diagonal cracks (3) and (4) at right end. At 30 000 lb. diagonal crack (6) appeared. At 32 000 lb.

TABLE 14.—*Continued.*

TESTS OF BEAMS WITH STIRRUPS.

Series of 1908.

All beams failed by diagonal tension unless otherwise noted.

Beam No.	Age days	Load at First Diagonal Crack pounds	Maximum Applied Load pounds	Stress in Longitudinal Reinforcement lb. per sq. in.	Vertical Shearing Stress lb. per sq. in.	Bond in Longitudinal Reinforcement lb. per sq. in	Tensile Stress in Stirrups lb. per sq. in.	Bond in Stirrups lb. per sq. in.
221.3	57	24 000	31 100	34 600	242	274	24 700	512
221.4	70	20 000	21 170	23 800	166	188	16 900	351
223.2	57	22 000	24 600	36 300	189	192	46 400	481
223.3	70	20 000	26 150	38 500	201	205	48 300	511
229.1†	63	20 000	22 000	43 500	255	259	26 000	540
229.2*†	92	20 000	25 400	50 000	292	296	29 800	618
229.5	72	13 000	13 400	20 100	159	164	12 750	337
229.8	60	14 000	26 100	37 700	200	204	16 000	423
233.3‡	72	18 000	20 850	38 300	159	203	26 000	539
233.4	66	18 000	26 300	38 200	201	201	25 800	536
240.1*	64	26 000	34 800	38 800	270	306	27 500	572
243.3	64	20 000	34 200	49 500	260	260	42 400	880

* Tension failure.

† Load applied at a single point 2 ft. from one support.

‡ Failure at the end not having stirrups.

crack marked (7) was noted at left end and vertical cracks marked (8) and (9) in middle third, and at 34 000 lb. vertical crack (10). At 36 000 lb. tension cracks in middle third were opening, diagonal cracks not opening much. Maximum load, 38 000 lb. Load dropped to 32 600 lb. failure occurring by tension in steel.

Beam No. 232.2. At 24 000 lb. numerous vertical cracks noted in middle third and diagonal cracks marked (1) at left end, but these did not open very wide. At 32 000 lb. diagonal cracks marked (2) were noted at right end. Maximum load, 40 300 lb. Failure occurred by tension in steel.

Beam No. 232.6. At 19 000 lb. a short diagonal crack marked (1) noted at right end at mid-depth of beam. At 20 000 lb. the above crack extended downward to bottom of beam and upward along fifth stirrup from end, a branch extending to load point. At 21 000 lb. crack marked (2) noted. Failure occurred by diagonal tension. Maximum load, 25 000 lb.

Beam No. 233.1. At 27 000 lb. a diagonal crack marked (1) was noted 21 in. to right of center and extended vertically 6 in. At 36 000 lb. a diagonal crack marked (2), 6 in. high, was noted 18 in. to left of center

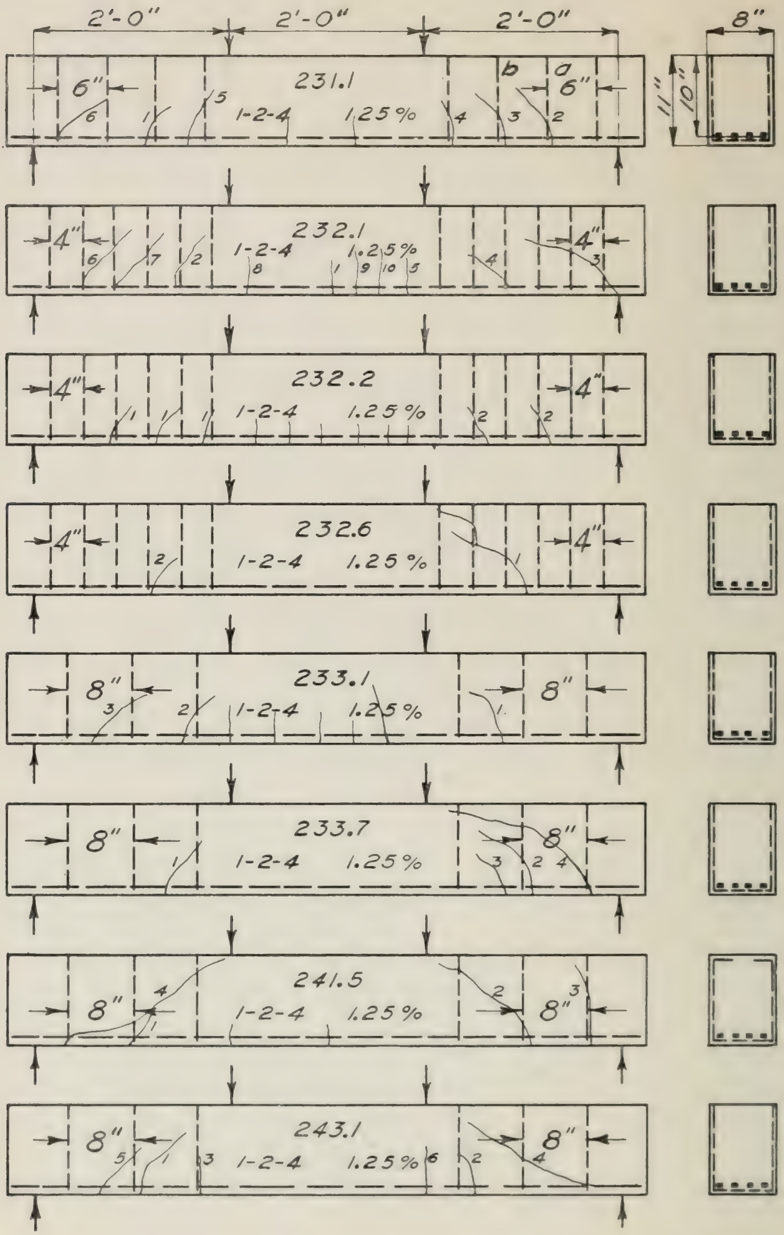

FIG. 16. DISPOSITION OF REINFORCEMENT AND POSITION OF CRACKS.

of beam. At this load a vertical crack 5 in. long appeared under left load, tension cracks 4 in. long were noted 6½ and 1 in. to left of center and a tension crack 3 in. high 3 in. to right of center. At 41 000 lb. a diagonal crack marked (3) extended vertically 5 in. At 43 200 lb. all cracks were opening. At maximum load, 43 300 lb. a tension crack 7 in. long noted 7 in. to right of center. Failure occurred by tension in steel.

Beam No. 233.2. At 20 000 lb. a diagonal crack appeared 9 in. to left of left load and extended vertically 4 in. At 28 000 lb. several vertical cracks were noted in middle third, and two diagonal cracks at right end. Diagonal crack noted at left end at load of 32 000 lb. Maximum load 34 700 lb. Failure occurred at right end by diagonal tension probably followed by slipping of bars. Middle stirrup at right end finally split out at near the maximum load on account of being too near the surface—about 1 in. center to surface.

Beam No. 233.7. At 23 000 lb. a diagonal crack marked (1) noted which extended vertically 5 in. At 24 000 lb. a diagonal crack marked (2), 7 in. high, noted. At 26 000 lb. diagonal cracks marked (3) and (4) appeared and extended vertically 4 in. The other cracks were opening up at this load. At 27 000 lb. the cracks were lengthening. At 27 200 lb., the maximum load, diagonal crack marked (4) opened and extended to load point. Load dropped to 22 000 lb., failure occurring by diagonal tension with slipping of stirrups.

Beam No. 235.1. At the maximum load of 14 500 lb. a diagonal crack 6 in. high appeared 13 in. to left of left load. Load dropped gradually, and at 13 000 lb. the crack was opening up rapidly toward load point.

Beam No. 235.5. Mixture was lean and concrete seemed poorly rammed at bottom. Failure occurred by diagonal tension. On one side the diagonal crack was observed at third stirrup from load. This stirrup was afterward found to be broken. Maximum load 6100 lb.

Beam No. 241.5. Stirrups bent in at top. At 18 000 lb. diagonal cracks marked (1) and (2) noted, (2) extending toward load point at 27 000 lb. At 22 000 lb. a crack 10 in. long marked (3) appeared. At 26 000 lb. a crack marked (4) was noted at left stirrup 2 in. above bottom of beam, extending to second stirrup from left end, and from there to load point. Maximum load 32 300 lb., failure occurring by diagonal tension.

Beam No. 243.1. At 26 000 lb. diagonal cracks marked (1) and (2) appeared. At 30 000 lb. a diagonal crack 6 in. high marked (4) noted at right end, 13 in. from load. At 32 000 lb. the cracks at left end were opening wider. At 34 000 lb. a diagonal crack marked (5) was noted 16 in. to left of left load and extended upward 6 in. Maximum load 44 300 lb., failure occurring by diagonal tension.

Beam No. 244.1. (See Fig. 17). At 18 000 lb. vertical cracks 4 in. long marked (1) noted 2½ in. to right of right load and 2½ in. to left of left load at stirrups. At 22 000 lb. a diagonal crack marked (2) appeared 11½ in. to left of left load and extended vertically 4½ in. At 23 700 lb. the crack at north end was opening wide. At 24 000 lb. a vertical crack marked (3), 6 in. high, was noted 3 in. to the left of center. Maximum load 24 100 lb. Tension crack marked (1) to left of load opened wide after the maximum was reached.

Beam No. 271.6. At 12 000 lb. vertical crack 5 in. long was noted 5 in. to right of right load. A short diagonal crack was also noted in lower third of beam on opposite side 7 in. to right of right load. At 13 800 lb. failure crack appeared suddenly, starting at right end 7 in. inside the support and extending to within 4 in. of load. The expanded metal web was not sufficient to give much resistance.

Beam No. 221.2. Three stirrups at right end were showing at surface. Concrete was poor. At 22 000 lb. a diagonal crack marked (1), 4 in. high, was noted 12 in. to right of left support. At 24 000 lb. diagonal crack

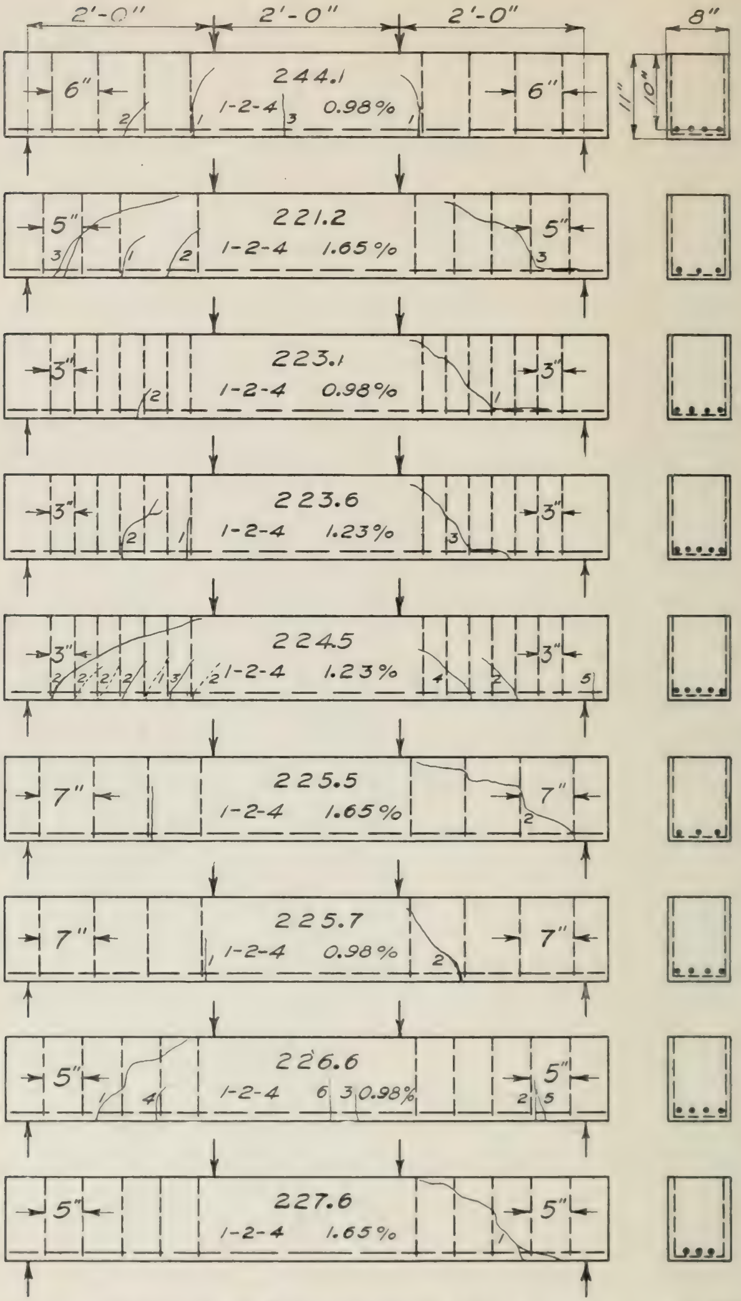

FIG. 17. DISPOSITION OF REINFORCEMENT AND POSITION OF CRACKS.

5 in. high marked (2), 6 in. to left of left load, was noted. At 26 000 lb. diagonal crack marked (3) appeared. Maximum load 26 000 lb., diagonal tension failure.

Beam No. 222.5. At 16 000 lb. vertical crack was noted 6 in. to left of left load. At 20 000 lb. one 5 in. to left of center and at 22 000 lb. 3 in. to right of center. At 20 000 lb. diagonal cracks were noted 10 in. to left of left load and 3½ in. to right of right load. Failure occurred by diagonal tension. Maximum load 23 700 lb. All the concrete broke away from bottom of second stirrup to left of left load. Reduced section could be plainly seen. Stirrup did not slip.

Beam No. 223.1. At 16 000 lb. diagonal crack 3 in. high marked (1) was noted. At 18 000 lb. this crack was 5 in. high and diagonal crack 4 in. high marked (2) was noted. Crack marked (1) opened wider at maximum load of 19 000 lb. and extended almost to load point. Failure by diagonal tension at right end.

Beam No. 223.5. At 19 000 lb. diagonal cracks were observed 8 in. to left of left load and 8 in. to right of right load. At 22 000 lb. a diagonal crack was noted 14 in. to right of right load. Maximum load 22 600 lb. Failure occurred by diagonal tension and failure crack was more nearly vertical than usual. Failure crack was limited to space between last three stirrups nearest the load. A loose stirrup was noted 6 in. to left of left load.

Beam No. 223.6. Diagonal cracks were noted 12 in. to left of left load and 9 in. to right of right load. Crack at right end extended almost to load point. Failure by diagonal tension at load of 21 000 lb.

Beam No. 224.5. At 14 000 lb. diagonal crack marked (1) was noted, at 15 000 lb. (2), at 16 000 lb. (3), and at 17 000 lb. crack (4). The cracks which started from the bottom of the stirrups headed for the center point of next stirrup toward load. Failure occurred by diagonal tension along diagonal crack at left end and several stirrups slipped at this end.

Beam No. 225.5. At 18 000 lb. crack marked (1) appeared. Failure occurred by diagonal tension along crack marked (2). Second stirrup from right end bulged out and drew down. Maximum load 22 000 lb.

Beam No. 225.7. At 17 000 lb. vertical crack 4 in. high marked (1) was noted and at 20 000 lb. diagonal crack 4 in. high marked (2). At 26 900 lb., the maximum load, the crack marked (2) extended almost to load point. Load dropped to 16 000 lb. Failure occurred by diagonal tension. Concrete around second stirrup to right of right load was very lean. Lower part of the stirrup on each side was exposed and stirrup slipped a little.

Beam No. 226 5. At 18 000 lb. the vertical crack 5 in. high was noted at stirrup 7 in. to left of left load. At 19 000 lb. a diagonal crack 4 in. high was noted 15 in. to right of right load. At 20 000 lb. the cracks were enlarging and at maximum load of 20 100 lb. a diagonal crack 6 in. high was noted 8 in. to right of right load. Load dropped to 11 300 lb.

Beam No. 226.6. At 16 000 lb. diagonal crack 3 in. high marked (1) was noted, at 18 000 lb. vertical crack along stirrup 5 in. high marked (2) and at 19 000 lb. the cracks marked (3) and (4). At 20 000 lb. diagonal crack marked (5) appeared and other cracks were enlarging. At maximum, load 21 000 lb., vertical crack marked (6) was noted; diagonal cracks were lengthening. Load dropped to 14 000 lb. and diagonal crack (1) was opening. Failure by diagonal tension at left end. The stirrups were quite close to sides of beam and were wrapped in paper for the lower 4 inches.

Beam No. 227.5. At 18 000 lb. small vertical cracks were noted 2 in. to right of right load, 4½ in. to left of left load, and at first stirrup 2 in. to left of left load on further side of beam. The latter crack was 4 in. long. Failure crack started at bottom of second stirrup 7 in. to right of right load, ran up stirrup 2½ in., then to first stirrup at a point 3¼ in. from top then upward along the stirrup. Maximum load 20 000 lb. Two stirrups were exposed at left end.

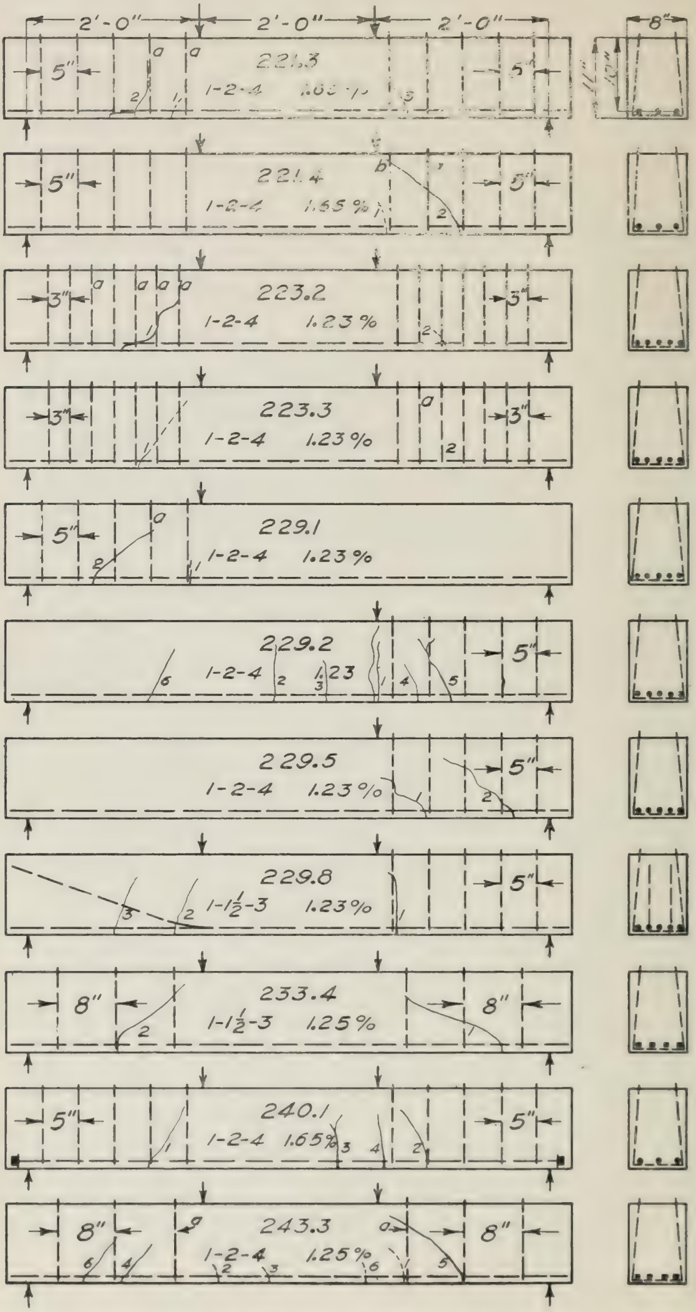

FIG. 18. DISPOSITION OF REINFORCEMENT AND POSITION OF CRACKS.

Beam No. 227.6. Cracks were noted on both sides of beam at 15 000 lb. No cracks noted at left end of beam. Failure was rather sudden and was due to diagonal tension. Third and fourth stirrups from right end were found to have slipped ⅛ or ¼ in. The stirrups were not well embedded, especially at north end where failure occurred. Maximum load 16 400 lb.

Beam No. 228.5. At 16 000 lb. a diagonal crack 5¼ in. high was noted 3 in. to left of left load. At maximum load, 17 500 lb., a diagonal crack 5½ in. high was noted 6 in. to right of right load. Failure occurred along the diagonal crack noted at 16 000 lb. The crack ended at bottom of beam at a point near first stirrup to left of load. First two stirrups at left end on further side of beam were showing at bottom. This fact did not affect the results, however.

Beam No. 228.6. At 19 000 lb. diagonal crack was noted 8 in. to right of right load on further side of beam and extended upward 4 in. At 20 000 lb. diagonal crack was noted 12 in. to left of left load and extended toward load point, starting at fourth stirrup from left end. One stirrup showed slightly at right end. Maximum load 21 400 lb., failure occurring by diagonal tension.

Beam No. 221.3. (See Fig. 18). At 24 000 lb. crack marked (1) noted at 27 000 lb. cracks marked (2) and (3), each being about 3 in. high. At 29 000 lb. cracks were lengthening. At 31 000 lb. the two stirrups marked (a) slipped as crack (2) opened. After the maximum load of 31 100 lb. the load fell off to 18 400 lb. and failure crack gradually opened.

Beam No. 221.4. At 20 000 lb. crack marked (1) noted. At 21 000 lb. stirrup marked (a) slipped. At maximum load, 21 170 lb., stirrup marked (b) slipped. Load fell off and crack gradually widened. Diagonal tension failure.

Beam No. 223.2. At 22 000 lb. crack marked (1) noted. At 24 000 lb. this crack was 7 in. high and crack marked (2) was noted. Maximum load 24 600 lb. Gradual failure by diagonal tension. The load was taken off and then applied again. It rose to 13 300 lb. then fell off to 12 200 lb. as failure crack opened and stirrups marked (a) slipped.

Beam No. 223.3. At 20 000 lb. crack marked (1) noted and at 23 000 lb. this crack was 7¼ in. high. Maximum load 26 150 lb. Failure was gradual and stirrup marked (a) slipped after beam started to fail.

Beam No. 229.1. Loaded at one point. At 20 000 lb. crack marked (1) noted 3 in. high. At 22 000 lb. diagonal failure crack marked (2) opened and stirrup marked (a) showed signs of slipping. Load dropped to 17 000 lb.

Beam No. 229.2. Also loaded at one point. At 14 800 lb. vertical crack marked (1) noted. At 18 000 lb. cracks marked (2), (3) and (4) noted. At 20 000 lb. crack marked (5) appeared and other cracks lengthened. At 24 200 lb. crack under load was 8 in. long and $\frac{1}{16}$ in. wide. Maximum load 25 400 lb., failure occurring by tension in steel. This shows a high resistance for the portion of the beam without stirrups.

Beam No. 229.5. Also loaded at one point. At 13 000 lb. crack marked (1) noted. At 13 400 lb., the maximum load, crack marked (1) was 4 in. high, and crack marked (2) was noted. Load fell off to 12 000 lb., failure occurring by diagonal tension. No signs of stirrups slipping and stirrups were not exposed.

Beam No. 229.8. Stirrups at one end only; at other end two bars bent up. At 14 000 lb. crack marked (1) was noted. At 20 000 lb. cracks marked (2) and (3) were noted, the former being 4 in. high and the latter 8 in. Cracks (1), (2) and (3) increased in length regularly as load was applied, and at 26 000 lb. cracks (2) and (3) were about 9 in. long and crack (1) 11 in. Crack (1) then widened appreciably. Maximum load 26 100 lb. Failure occurred at the end having stirrups and took place slowly. Whether slip of stirrup along longitudinal bar or slip of the latter occurred is not known. Concrete was rich mixture.

Beam No. 233.4. At 18 000 lb. cracks marked (1) and (2) were noted. Up to maximum load of 26 300 lb. the cracks gradually lengthened and failure occurred by diagonal tension.

Beam No. 240.1. This beam had nuts and washers at ends of longitudinal rods. At 26 000 lb. cracks marked (1) and (2) appeared. At 33 000 lb. cracks marked (3) and (4) were noted and other cracks were lengthening. Failure occurred by tension in steel at 34 800 lb. followed by crushing of concrete. Stirrups did not slip.

Beam No. 243.3. At 20 000 lb. crack marked (1), 3 in. high, appeared. At 21 000 lb. crack marked (2) noted near left load point. At 23 000 lb. crack marked (3), 3 in. high, appeared. At 26 000 lb. diagonal crack marked (4), 4½ in. high noted at left end of beam. Crack marked (1) was 7 in. high at this load. At 30 000 lb. crack marked (5) was noted. At 34 000 lb cracks marked (6) and (7) were noted, the other cracks were lengthening and at this load stirrups marked (a) had slipped. Maximum load was 34 200 lb., failure occurring by diagonal tension.

36. *Stresses in Stirrups.*—The assumption in the calculations of an effective bond area given by six-tenths of the length of the stirrup is arbitrarily made, but it gives a common basis of comparison. It will be seen in Table 14 that the tensile stresses in the stirrups resulting from this calculation are generally low, though in some cases they run well above the yield point of the steel, and even above its ultimate strength. Thus, the calculated stresses in the high carbon corrugated bar stirrups used in No. 231.1, 231.5 and 231.6 (93 000 to 104 000 lb. per sq. in.) and the stresses in the mild steel corrugated bar stirrups used in No. 232.1 and 232.2 (72 000 and 78 000 lb. per sq. in.) are higher than the elastic limit and ultimate strength of the steel. The bond stresses in many cases are also much above what would be expected to cause slip. These calculated results, and other tests obtained in this laboratory and elsewhere seem to corroborate the view expressed on page 19 that the stress actually developed in stirrups is less than that calculated by equation (21) and that a part of the shear is carried through the concrete of the top of the beam. The actual proportion taken by the stirrups has not been established, but it seems that the stress can not be more than two-thirds or three-fourths of the amount obtained by the formula. On this basis the calculation for tension and bond in stirrups would be made by using say two-thirds of the external vertical shear instead of the full amount

37. *Comparison of Results.*—As already stated, slip of stirrups and insufficient bond resistance were in many cases the immediate cause of diagonal tension failures, and therefore bond resistance

of stirrups may be considered a critical stress. If we omit special conditions like poor concrete, exposed stirrups, and unsymmetrical loading the following statements of stresses calculated by the methods already described may be made. The 1907 tests with longitudinal reinforcement of plain round rods and with smooth stirrups gave values of the vertical shearing stress *v* ranging from 154 to 203 lb. per sq. in. and bond values in the longitudinal reinforcement from 196 to 230 lb. per sq. in. The calculated tensile stress in the stirrups ranged from 15 000 to 52 000 lb. per sq. in., and the calculated bond in the stirrups from 326 to 443 lb. per sq. in. With deformed bars as longitudinal reinforcement and with smooth stirrups, the vertical shearing stress *v* developed was 208, 216 and 336 lb. per sq. in. and the bond developed in the longitudinal bars 208, 216 and 336 lb. per sq. in. The calculated stress in the stirrups ranged from 21 600 to 36 500 lb. per sq. in., and the bond developed in the stirrups 563 lb. per sq. in. Where bent stirrups were used, the value of the vertical shearing stress *v* was 246 and 224 lb. per sq. in., the bond developed in the longitudinal bars 246 and 224 lb. per sq. in., and the bond in the stirrups 834 and 760 lb. per sq. in. In beams with stirrups made of corrugated bars, the vertical shearing stress developed ranged from 170 to 328 lb. per sq. in., the calculated tensile stress in the stirrups reached 104 000 lb. per sq. in., and the bond 1088 lb. per sq. in.

In the 1908 tests, in beams with plain longitudinal reinforcement and with smooth stirrups the vertical shearing stress developed was 166 to 292 lb. per sq. in. and the bond in the longitudinal bars 188 to 296 lb. per sq. in. Calculations give a tensile stress as high as 48 000 lb. per sq. in., and bond stresses of 351 to 618 lb. per sq. in., in the stirrups. In the beam with corrugated stirrups the vertical shearing stress developed was 200 lb. per sq. in., and in the beam having two longitudinal bars bent up at one end and having corrugated stirrups at the other, 200 lb. per sq. in. vertical shearing stress was developed and 423 lb. per sq. in. bond stress in the stirrups. In No. 243.3, having longitudinal reinforcement of deformed bars and smooth stirrups, the vertical shearing stress was 260 lb. per sq. in. and the bond stress in the stirrups 880 lb. per sq. in. The 1908 beams were made of somewhat better concrete and the results with the smooth stirrups are as high as are to be expected. No. 240.1 (with nuts and washers on the ends of the longitudinal reinforcement) gave a vertical shearing stress of 270 lb. per sq. in., which is higher than the results of similar beams without anchorage. Stirrups with bent-in ends have many advantages. Much may be said, also, in favor of deformed bars for stirrups, though of course it is plain that mild steel is best for this purpose. Attention is called to the fact that a value of 296 lb. per sq. in. for the calculated bond resistance with plain round rods as longitudinal reinforcement was obtained in one beam.

38. *Effect of Poor Concrete.*—Beams No. 235.1, 235.2, 235.5 and 235.6, made of 1–5–10 concrete, were tested to study the effectiveness of stirrups with poor concrete. The results vary greatly. No. 235.2 sustained a fair load, but No. 235.5 which gave evidence of very poor concrete, proved to be very weak. It is evident that after the concrete begins to crack badly through diagonal tension, the stirrups are ineffective in giving web strength. There was no evidence of slip of stirrups in these beams.

It was also evident in beams of 1–2–4 mix that quality of concrete affects the effectiveness of stirrups. In sets containing the same arrangement of reinforcing, the higher values obtained are in beams of stronger concrete, as shown by the appearance of the concrete or by auxiliary tests.

However, even with the very lean mixtures the failure of the beam was slow and quite in contrast with the failures of beams of the same mixture not provided with web reinforcement.

39. *Effect of Unsymmetrical Loading.*—Beams No. 229.1, 229.2, 229.5 and 229.8 were made with stirrups in one end of the beam but with none in the other, and the first three were tested with a single concentrated load applied at 2 feet from the support next to the end having stirrups. This arrangement was planned to learn the effect of unsymmetrical loading on beams without web reinforcement, as when a concentrated load is placed at one end of the beam and there are no stirrups in the middle portion, and also to get information on the action of beams with web reinforcement and unsymmetrical loading. No failures occurred at the middle or at the end not having stirrups, although the stresses developed (one-half of the vertical shearing stress given in the table) in the middle and unstirruped end of the beam ranged as high as those found at failure in the series without web reinforce-

ment. It seems evident that concentrated, unsymmetrical loading gives results comparable with those found by symmetrical loading.

In Beam No. 229.8 the end which was not provided with stirrups had instead two bars bent up as shown in Fig. 18. Failure occurred near one stirrup, the crack being nearly vertical. As this was rich concrete, and the concrete did not break up, and as the stresses in the stirrups were small, it would seem as if slip of longitudinals may have contributed to failure. It is classed, however, as a diagonal tension failure. In this beam the web resistance given by stirrups and by bent rods appears to be nearly the same.

40. *Proportioning of Stirrups.*—It is evident that some form of web reinforcement may well be used whenever the value of the vertical shearing stress under working conditions is more than one-third or one-fourth of the values given on page 46 for the quality of concrete assured by the conditions of construction, and also in beams developing even lower stresses if there is an uncertainty in the web strength or in the quality of concrete or if the method of applying the load or the nature of the structure makes such a safeguard desirable. The effectiveness of stirrups in providing additional web resistance is brought out in the tests. The insurance of slow failure given by stirrups is itself an advantage. The spacing of the stirrups should not be more than three-quarters or eight-tenths of the depth of the beam.

From the tests and discussion, it appears that as a tentative method it is allowable to consider that for good concrete one-third of the vertical shear is carried through the concrete in the upper part of the beam and two-thirds go to produce stresses in the stirrups. Using then, two-thirds of the total vertical shear as the V of equation (21), p. 18, the ordinary working stresses for tension and bond may be used in the calculations for stirrups. With these assumptions, a length equal to six-tenths of the depth of the beam may be used in the calculations for bond.

Even for well proportioned web reinforcement the use of high values of v is to be discouraged, and strengths should not be accepted unless tests of the same class of beams made under the same conditions of construction give correspondingly high strengths. It may be expected, too, from analogy to the results in beams without web reinforcement, that when stirrups are used, stiff beams may be counted on better to resist web stresses than those with lighter reinforcement.

Tests with a combination of stirrups and of bending up of part of the reinforcing bars were not made but it is evident that such an arrangement, say to bend up one-half of the bars, gives added web resistance. The proportion of the diagonal tension taken by the bent-up bars and by the stirrups can not be calculated. In such cases the bond developed in the longitudinal reinforcement should be taken into consideration and it is quite possible that the bond resistance obtained with deformed or anchored bars may be advantageous. There is need of experimental work along these lines.

41. *Web Reinforcement of Expanded Metal.*—It was not expected that Beams No. 271.5 and 271.6 would carry higher loads than beams without web reinforcement, since the amount of material in the web was quite inadequate for web stresses and since the metal was not well placed. The beams are included in the list, however, as an example of the inefficient web reinforcement which has been proposed or used without either experimental or analytical verification of its value.

D. GENERAL COMMENTS ON WEB RESISTANCE

42. *General Comments.*—No effort will be made to review the discussion or summarize results, but a few general statements may be made.

Failures by diagonal tension in beams without web reinforcement are especially objectionable, since, as in the case of tension tests of concrete, the failure may occur without warning. Besides, although the effect of repeating the application of the load after a diagonal crack has formed has not been established, final failure undoubtedly will occur after many applications at a load much lower than that which would cause failure on first application.

In beams without web reinforcement, web resistance depends upon the quality and strength of the concrete. Cement makes a simple and effective strengthening agent. The effect of quality and strength of concrete is very marked. Even where web reinforcement is used, quality of concrete is an important element.

The stiffer the beam the larger the vertical shearing stress which may be developed. Short, deep beams give higher results than long, slender ones, and beams with a high percentage of reinforcement than beams with a small amount of metal. This difference may be due to the relation of diagonal tension to shearing stress, to the difference in opportunity for formation of vertical tension cracks, or to such a cause as a difference in amount of distortion of section.

As beams ordinarily have less than 1% reinforcement, the web strength of such beams may be expected to be less than that of the beams herein described.

There is a considerable increase of web strength at the earlier ages, but not much additional web strength may be counted on under laboratory conditions after 60 days. Care should be exercised that ample time is given for beams to acquire sufficient web strength before loads are applied.

The loads carried by beams with all bars bent up or inclined in the outer thirds of their length did not differ much from those with the bars all straight, but the failure is slower and warning is given. The formation of a vertical crack and the splitting of the concrete along the inclined part of the bar are characteristic of the failures.

Beams with inclined bars firmly anchored at their ends gave high web resistance and showed indications of arch action. This form of construction seems to give insurance against failure at low loads through defective concrete or insufficient bond.

The arrangement of bending up part of the bars and leaving part straight developed a good web strength and secured slow failures. This method will be particularly satisfactory when the number of bars is large enough to permit the spacing of the inclined bars at frequent intervals through the part of the beam where high web resistance is needed. A proper distribution of the diagonals is important.

The Cummings' reinforcement gave high web strength. The distribution of the diagonals fills the requirements above mentioned, a lateral connection is provided, and the main bars are carried to the end of the beam.

Beams provided with U-shaped stirrups which passed under straight reinforcing bars generally gave high web resistance, and slow failures were characteristic of the tests. The importance of quality of concrete is also apparent in these tests. Adequate bond resistance is essential. The amount of web resistance which may be developed even with carefully arranged stirrups is limited, the limit depending upon the quality of the concrete.

Stirrups do not come into action, at least not to any great extent, until a diagonal crack has formed. After such a crack has formed, the stirrups will take stress from the beginning on a second application of the load.

The tests and calculations go to show that under the maximum loads applied to the beams the stirrups are not stressed to an amount necessary to take the entire vertical shear. The use of a fractional part of the total vertical shear like two-thirds for application in the formulas seems to be warranted.

Considerable variation in results in beams of the same make-up was found. This is to be expected in web resistance. An even greater variation is probable under conditions of practice.

Low working stresses in web resistance are to be commended and ample provision for web strength should be made.

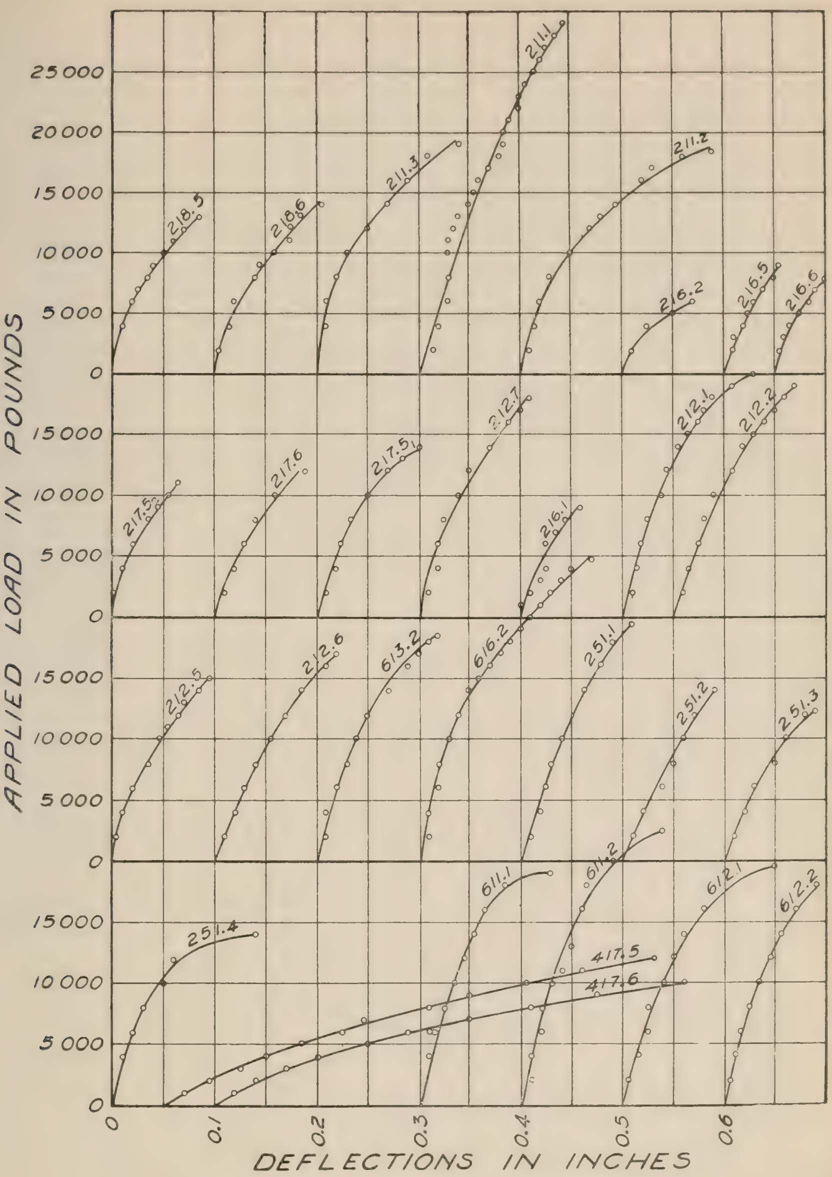

FIG. 19. LOAD-DEFLECTION DIAGRAMS.

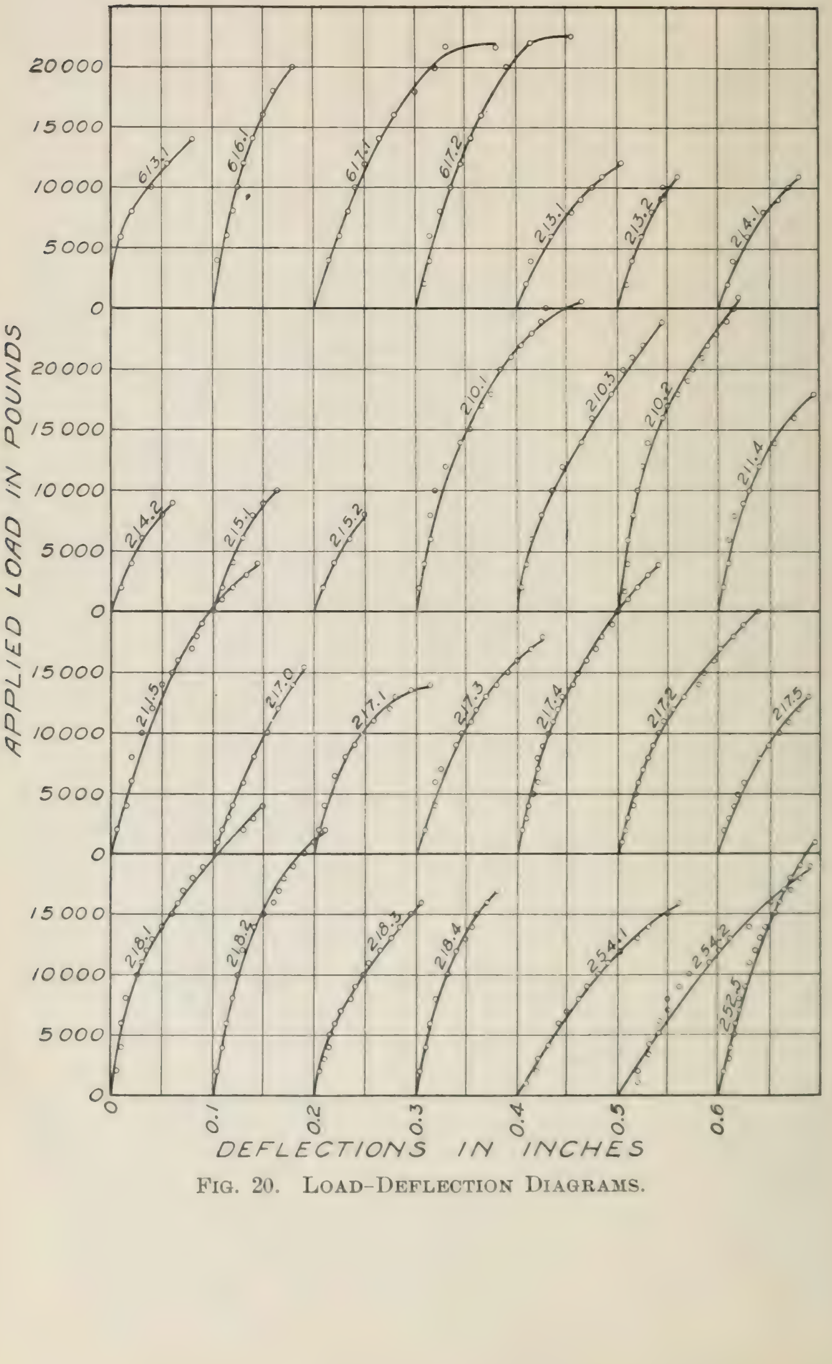

FIG. 20. LOAD-DEFLECTION DIAGRAMS.

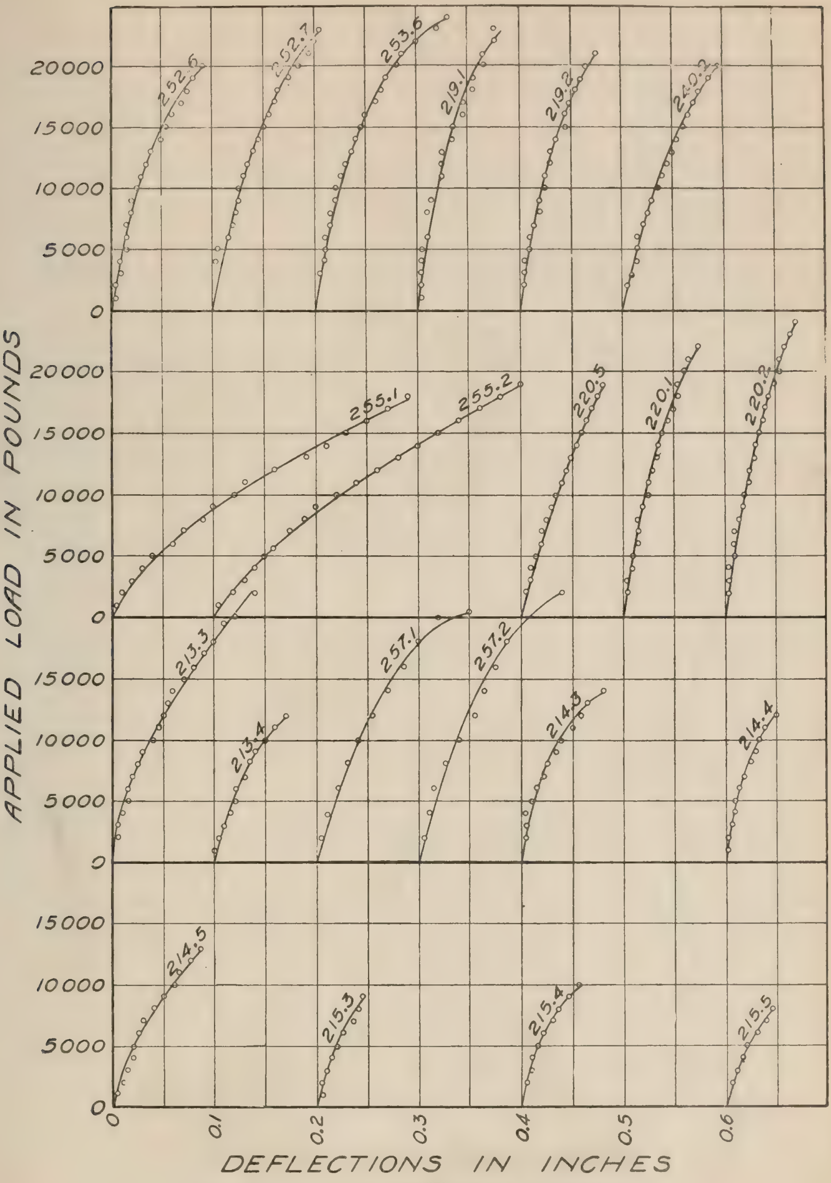

FIG. 21. LOAD-DEFLECTION DIAGRAMS.

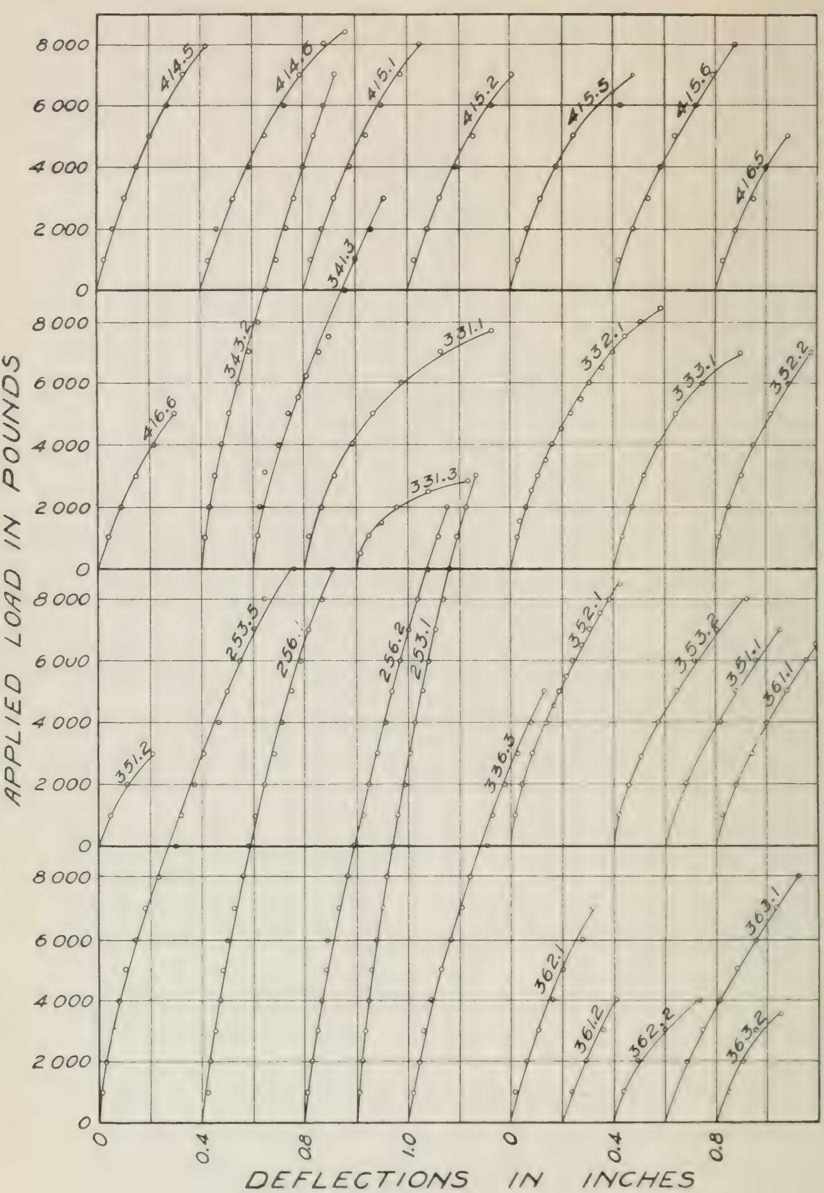

FIG. 22. LOAD-DEFLECTION DIAGRAMS.

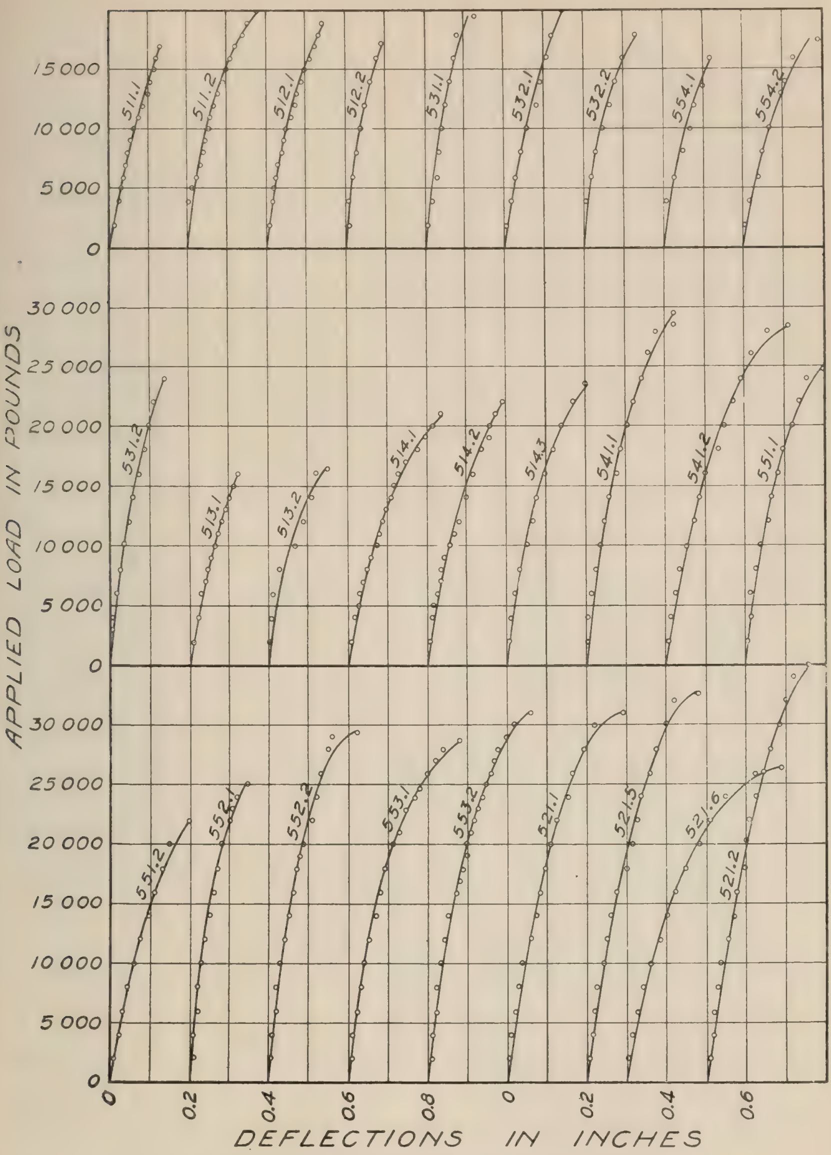

FIG. 23. LOAD-DEFLECTION DIAGRAMS.

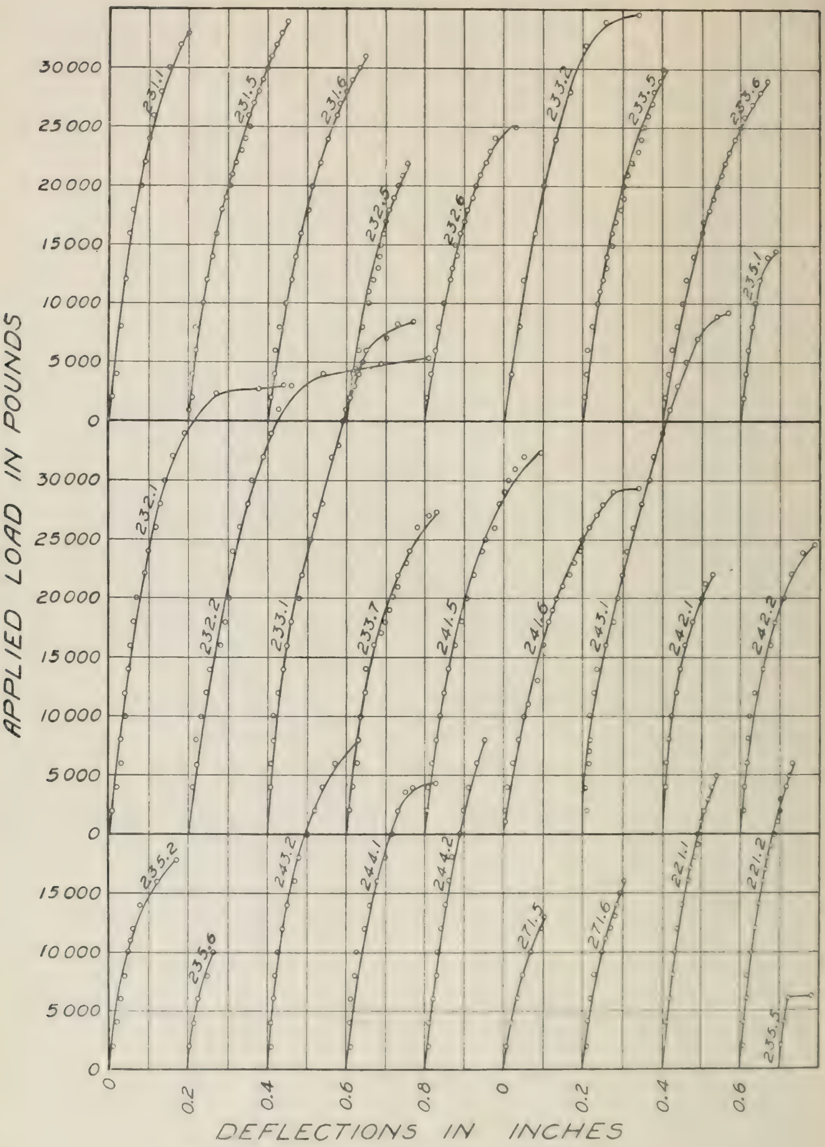

FIG. 24. LOAD-DEFLECTION DIAGRAMS.

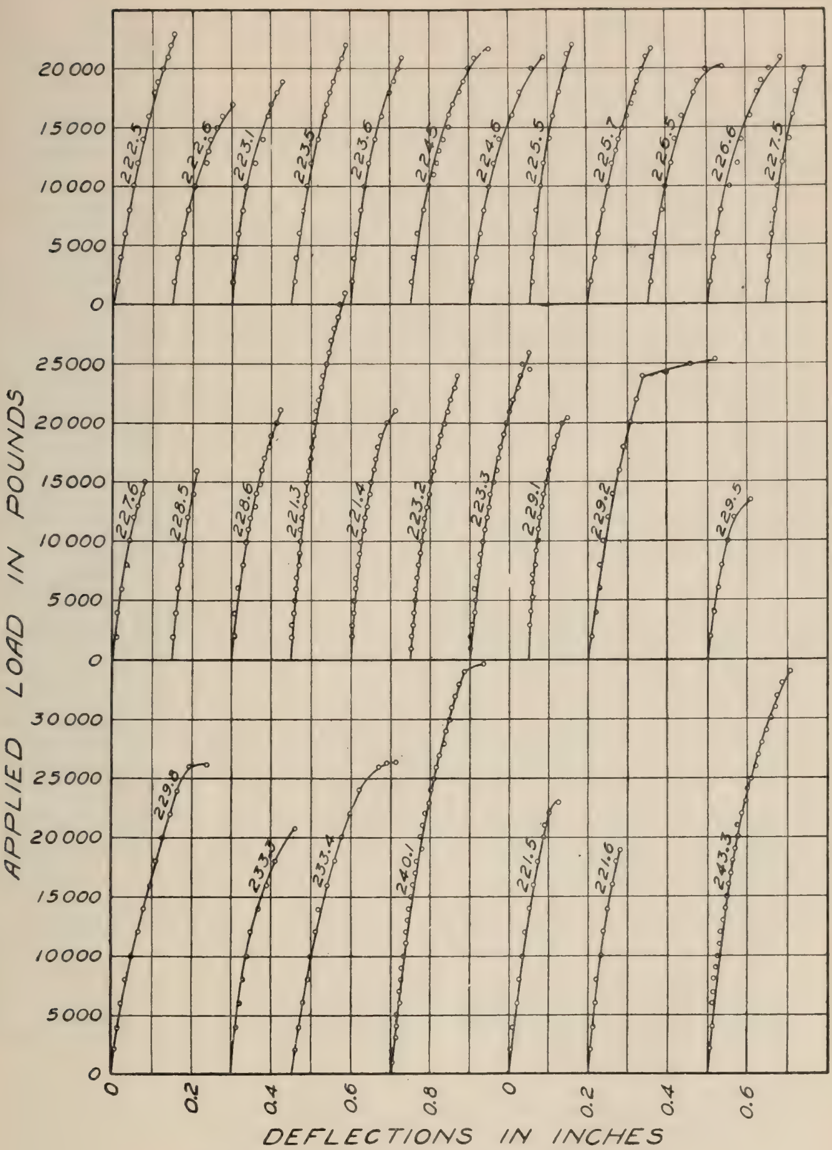

FIG. 25. LOAD-DEFLECTION DIAGRAMS.

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UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 30 FEBRUARY, 1909

ON THE RATE OF FORMATION OF CARBON MONOXIDE IN GAS PRODUCERS

BY J. K. CLEMENT, PHYSICIST, U. S. G. S., TECHNOLOGIC BRANCH, ASSISTED BY L. H. ADAMS, JUNIOR CHEMIST, U. S. G. S., TECHNOLOGIC BRANCH; APPENDIX BY C. N. HASKINS, ASSISTANT PROFESSOR OF MATHEMATICS, UNIVERSITY OF ILLINOIS.

I. INTRODUCTORY STATEMENT.

The rapid advance in the use of producer gas in recent years has given rise to a demand for a more accurate knowledge of the processes taking place in the fuel bed of the producer and the effect on these processes of certain variations in the conditions of operation. The primary function of the gas producer is to transform solid fuel into a more readily combustible gaseous fuel This transformation, which is relatively slow, consists of the following processes:

1. The distillation of the volatile hydro-carbons from the freshly fired fuel at relatively low temperatures.

2. The combustion of fuel by combination with the oxygen of the air.

3. The formation of producer gas proper in accordance with the equations:

$$\text{I.}\quad CO_2 + C = 2\,CO,$$
$$\text{II.}\quad H_2O + C = CO + H_2.$$

The first of these reactions, the formation of carbon monoxide, is the one with which the present investigation deals. The problem proposed is in broad terms to determine the factors that govern the production of CO in the gas producer; and the effect of the temperature and of the time of contact of the gas and carbon on the percentage of CO in the producer gas. The question of the effect of temperature was brought forth by certain experiments made by one of the writers at the Fuel Testing Plant of the U. S. Geological Survey at the Jamestown Exposition, in which it was found that the temperature in the fuel bed of the gas producer varies greatly from one portion of the bed to another. In order, therefore, to ascertain the conditions of temperature most favorable to the efficient operation of the producer, it becomes necessary to determine the temperature requisite for the formation of carbon monoxide and hydrogen in accordance with the reactions quoted in the preceding paragraph.

A study of the conditions for the reduction of CO_2 by carbon seems desirable from another consideration. A small amount of CO is invariably contained in the flue gases of boiler furnaces. It was hoped, therefore, that the investigation might furnish an explanation of the formation of CO in boiler furnaces and perhaps suggest a means of preventing such formation.

The investigations herein described were made in, and with the facilities of, the Physical Laboratory of the University of Illinois.

II. Fundamental Equations.

According to the law of chemical mass action, a chemical reaction, as for example the reaction expressed by the equation

$$C + CO_2 = 2\,CO,$$

proceeds in one direction until equilibrium is established and then stops; and when the system is in equilibrium there is for a given temperature a certain constant relation between the amounts of the components entering into the reaction. Thus, in the system under consideration, let

$[CO]$ = the concentration of CO in gram molecules[1] per liter,

$[CO_2]$ = the concentration of CO_2 in gram molecules per liter;

then for equilibrium, the relation

---

[1] A gram molecule of a substance is a weight of the substance in grams numerically equal to the molecular weight. Thus a gram molecule of CO is 28 grams, one of CO_2 is 44 grams, etc.

$$\frac{[CO]^2}{[CO_2]} = \text{constant} = K \tag{1}$$

must be satisfied.

The relation (1) may be thrown into another form as follows:

Let $100\ x$ = per cent of CO in the gas by volume;
$100\ (1 - x)$ = per cent of CO_2 in the gas by volume;
p = pressure in atmospheres;
T = absolute temperature;
R = absolute gas constant = 0.0821 for the system of units here employed;
n = number of gram molecules of the gas under consideration;
v = volume of gas in liters.

The characteristic equation of gases is

$$pv = nRT$$

from which

$$\frac{n}{v} = \frac{p}{RT}$$

Now xn and $(1 - x)n$ are respectively the numbers of gram molecules of CO and CO_2 in the gas; hence the concentrations of CO and CO_2 are respectively

$$[CO] = \frac{xn}{v} = \frac{xp}{RT}$$

$$[CO_2] = \frac{(1 - x)n}{v} = \frac{(1 - x)p}{RT}$$

Placing these values in (1), the resulting equation is

$$\frac{x^2}{1 - x}\,\frac{p}{RT} = K \tag{2}$$

If the pressure and temperature are kept constant, the factor $\frac{p}{RT}$ is a constant, and (2) may be written

$$\frac{x^2}{1 - x} = \frac{KRT}{p} = K' \tag{3}$$

where K' is a new constant.

When CO_2 gas is maintained in contact with carbon at constant temperature and pressure the two will react rapidly at first and then more slowly until the amount of CO formed is 100 x per cent of the total, where x is given by equation (3).

The relation expressed by (1) may be considered as a special case of a more general law. According to the theory of the kinetics of reactions now generally accepted in reversible reactions, two reactions take place simultaneously, one from left to right and one from right to left. In the reaction

$$CO_2 + C = 2\,CO$$

the velocity of the reaction from left to right, that is, the rate of formation of CO, is at any instant proportional to the number of CO_2 molecules in the unit volume; thus denoting the velocity by v,

$$v = k_1[CO_2].$$

Similarly the velocity of the reaction from right to left, that is, the rate of formation of CO_2, is proportional to the square of the number of CO molecules in a unit volume. Hence

$$v' = k_2[CO]^2$$

The increase in the number of CO molecules per unit volume in the time dt is the difference of the two velocities v and v'; that is,

$$\frac{d\,[CO]}{dt} = v - v' = k_1\,[CO_2] - k_2\,[CO]^2 \qquad (4)$$

As [CO] the number of gram molecules of CO in the unit volume increases and $[CO_2]$ the number of gram molecules of CO_2 decreases, the velocity $\frac{d\,[CO]}{dt}$ will become smaller and smaller until finally [CO] and $[CO_2]$ become constant, that is, the system attains equilibrium. In this case we have, therefore,

$$\frac{d\,[CO]}{dt} = v - v' = 0$$

whence $$k_1\,[CO_2] = k_2\,[CO]^2. \qquad (5)$$

That is, the number of CO_2 molecules formed in a given time is equal to the number that are decomposed to form CO. The last equation may be written

$$\frac{[CO]^2}{[CO_2]} = \frac{k_1}{k_2} = K. \qquad (6)$$

K is called the *equilibrium constant.*

Equation (4) giving the rate of formation of CO may be modified as follows:

Let $100\,a$ = per cent of CO_2 by volume at the beginning of the reaction, that is, when $t = 0$,

$100\,x$ = per cent of CO by volume after the time t has elapsed.

At the beginning of the reaction, that is when $t = 0$, there is no CO, hence $x = 0$. If now n is the number of gram molecules of the gas when $t = 0$, then na is the number of gram molecules of CO_2, and the concentration of the CO_2 is therefore

$$[CO_2] = \frac{n\,a}{v}.$$

But since $pv = n\,R\,T$, this relation may be written

$$[CO_2] = \frac{a\,p}{R\,T} = M \text{ gram molecules per liter.}$$

At the time t suppose m gram molecules per liter of CO to have been formed. This involves the disappearance of $\frac{m}{2}$ gram molecules per liter of CO_2, leaving $M - \frac{m}{2}$. The number of gram molecules of gas is now

$$n\,(1 - a) + \left[\ M - \frac{m}{2} + m\ \right] v$$

$$= n\,(1 - a) + \left(M + \frac{m}{2}\right) \frac{n\,a}{M}$$

$$= n\,(1 + \frac{m\,a}{2\,M})$$

$$= n\,(\,1 + \frac{m}{2}\,\frac{RT}{p}\,),$$

and the volume of the gas is therefore increased from v to $v\,(\,1 + \frac{m}{2}\,\frac{RT}{p})$. The concentrations at the time t are therefore

$$[CO] = \frac{m}{1 + \frac{m}{2}\,\frac{RT}{p}}, \tag{7}$$

$$[CO_2] = \frac{M - \frac{m}{2}}{1 + \frac{m}{2}\,\frac{RT}{p}}. \tag{8}$$

But since 100 x per cent of the gas is CO by volume the concentration of the CO is also given by the relation

$$[CO] = \frac{xp}{RT}. \tag{9}$$

Combining the two expressions for [CO] given by (7) and (9), we obtain.

$$m = \frac{2x}{2 - x}\;\frac{p}{RT},$$

and introducing this expression for m in (8), the result after slight reduction is

$$[CO_2] = (a - \frac{a + 1}{2}\,x)\,\frac{p}{RT}. \tag{10}$$

Introducing in equation (4) the expressions for the concentrations given by (9) and (10), the result is

$$\frac{d[CO]}{dt} = k_1\,\frac{p}{RT}\,(\,a - \frac{a + 1}{2}\,x\,) - k_2\,\left[\frac{p}{RT}\right]^2 x^2. \tag{11}$$

But from (9)

$$\frac{d[CO]}{dt} = \frac{p}{RT}\;\frac{dx}{dt},$$

whence

$$\frac{dx}{dt} = k_1 \left(a - \frac{a+1}{2} x \right) - k_2 \frac{p}{RT} x^2.$$

Replacing the constant $k_2 \frac{p}{RT}$ by a single symbol k'_2, the final equation for the reaction velocity is

$$\frac{dx}{dt} = k_1 \left(a - \frac{a+1}{2} x \right) - k'_2 x^2. \qquad (12)$$

The integration of the differential equation (12) offers no great difficulty.

The determination of the constants k_1 and k_2 seems to have been made hitherto by assuming the value of the ratio $\frac{k_1}{k'_2}$. This method is applicable when the equilibrium conditions are readily realized. As, however, this is not the case in the present reaction it has been necessary to devise a method for the determination of k_1 and k'_2 from two or more pairs of simultaneous observations of x and t. It turns out that the method is applicable not only to the reaction in question, but also to the most general incomplete reactions of the second order.

The great difficulty of realizing, with certainty, the condition of the equilibrium in reactions like the one under consideration, makes it highly desirable, therefore, to obtain a general solution of the differential equation, without introducing a particular numerical value for the ratio $\frac{k_1}{k'_2}$. We are indebted to Prof. C. N. Haskins for the following solution, the developments of which will be found in the appendix:

$$x = \frac{4\,a}{a+1} \; \frac{\gamma \tanh \alpha t}{1 + \gamma \tanh \alpha t}. \qquad (13)$$

In equation (13) α and γ are determined by the relation

$$k_1 = \frac{4\alpha\gamma}{a+1},$$

$$k'_2 = \frac{a(a+1)}{4a\gamma}(1 - \gamma^2).$$

When the initial percentage of CO_2 is 100, then $a = 1$,

$$\frac{dx}{dt} = k_1(1 - x) - k'_2 x^2,$$

and
$$x = \frac{2\gamma \tanh \alpha t}{1 + \gamma \tanh \alpha t}. \tag{14}$$

In the case of the gas producer the value of a is about 0.21.

III. Boudouard's Experiments.

An elaborate series of determinations of the amount of CO formed at different temperatures has been made by O. Boudouard.[1] Boudouard's observations were made at 650°, 800° and 925° C. In his experiments at 650° and 800° glass tubes containing charcoal, coke, retort carbon or lamp black were filled with CO_2, heated to the temperature of the experiment and then sealed. The tubes were maintained at constant temperature until equilibrium was reached, that is, when further heating at the same temperature produced no increase in the percentage of CO present. At 650° the heating was continued for twelve hours before equilibrium was attained. At 800° equilibrium was reached in one hour in the tubes containing charcoal and in two and one-half hours in those containing lamp black. With coke and retort carbon the process was not complete at the end of nine hours. In the experiment at 925° the carbon was heated in a porcelain tube, through which was passed a stream of CO_2 gas. The average time of contact between CO_2 and carbon calculated from the data given

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[2] O. Boudouard, *Comptes Rendus de l'Academie des Sciences.*
Vol. 128, page 824, 154; 1899.
Vol. 131, page 1204, 1900.
Vol. 130, page 132, 1900.
Bulletin Soc. Chim., Paris, Vol. 21, 1901.
Bulletin Soc. Chim., Paris, Vol. 25, 1901.
Ann. de Chimie et de Physique, Vol. 354, 1901.
See also Haber, *Thermodynamics of Technical Gas Reactions*. 1908, p. 311.

in Boudouard's account of his experiments was approximately 30 seconds.

A summary of Boudouard's results is given in the following table:

TEMPERATURE C.°	PER CENT OF CO_2	PER CENT OF CO
650.	61.	39.
800.	7.	93.
925.	4.	96.

These values have been made the basis of computation by many writers on the chemistry of combustion and of the water gas reaction and especially in treatises on the gas producer.

In the first references to Boudouard's work which came to the attention of the writers, no notice was taken of the remarkably low reaction velocity of the formation of CO from CO_2 and carbon, and of the great length of time required to obtain the percentages of CO that are given in the preceding table. In at least one case the values shown above were offered as representing the quality of gas that should be obtained in the gas producer at the temperatures given. The writers were therefore led to regard Boudouard's figures as defining the relative proportions of CO_2 and CO that should be formed in a gas producer at various temperatures of the fuel bed.

The experiments which form the subject of this paper had originally as their object the confirmation of Boudouard's results as well as a continuation of them at higher temperatures. Preliminary experiments made by Dr. C. S. Hudson demonstrated that the amount of CO formed at a given temperature depends largely on the time of contact or in other words on the rate of flow of the gas through the fuel bed. Apparently Boudouard's results represent limiting values, which can be obtained only with a very low gas velocity. In order to ascertain the conditions for the formation of CO in producer furnaces, it is necessary, therefore, to determine the rate of formation of CO from CO_2 and carbon at various temperatures; that is, to determine the amount of CO formed with different rates of flow of the gas through the fuel bed.

IV. Method of Experiment.

The arrangement of the apparatus is shown in Fig. 1, 2, and 3. A porcelain tube of 1.5 cm inside diameter, 60 cm long, and glazed on the outside was filled with charcoal, coal, or coke and heated in an electric furnace. The furnace, which was designed especially for this investigation, is shown in detail in Fig. 3. It has been operated continuously for a period of six months at temperatures of from 800° to 1200°, and even 1300° C. The temperature inside the porcelain tube could be maintained at any value up to 1300° C with no fluctuations greater than 1° or 2°. The heating coil consists of a coil of No. 13 nickel wire, wound with eight turns per inch on an electrical porcelain insulating tube of 38 mm inside diameter and 35 cm long. At either end of the coil

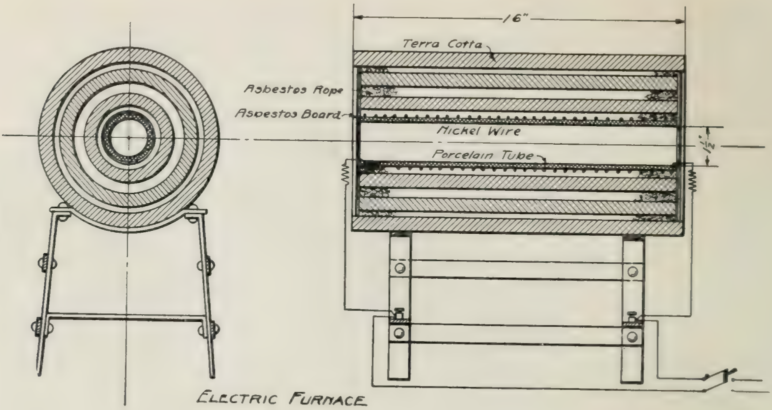


Fig. 1

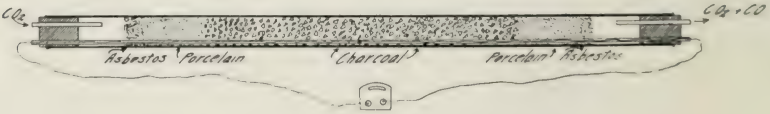


Fig. 2

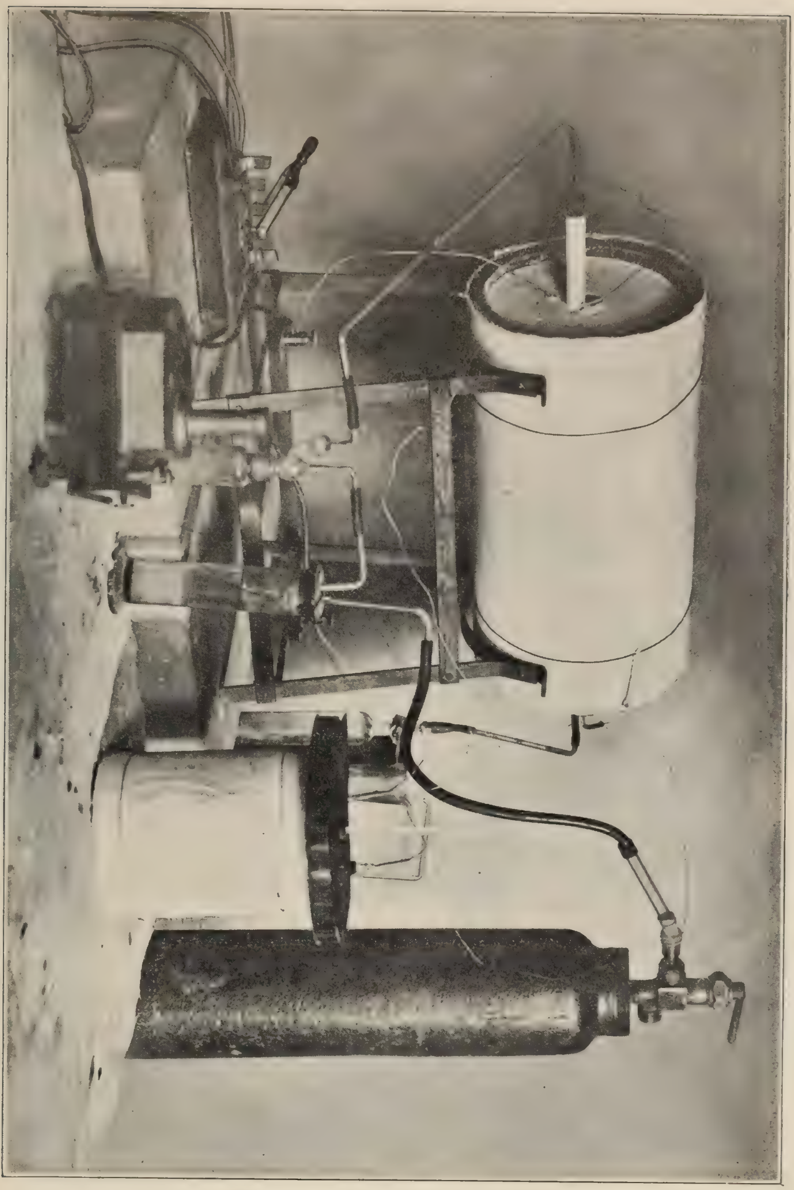


Fig. 3

the number of turns was increased slightly to compensate for the cooling effect of the end at the furnace. As a protection against corrosion, the coil was painted over with a thin layer of magnesite cement—a material that is capable of withstanding very high temperatures. The heating tube was then mounted inside of and concentric with several terra cotta pipes and the spaces between the pipes were filled with light calcined magnesia. The cost of the material used in the furnace and the amount of labor required were very small. A temperature of 1000° C could be maintained by the expenditure of 600 watts.

The temperature inside the porcelain tube was measured by means of a platinum platinum-rhodium thermocouple (see Fig. 2) and a Siemens & Halske milli-voltmeter. As the thermo-electric height of the couple fell slightly with use at high temperature —due probably to the reducing action of CO gas on the insulating tubes and the consequent contamination of the couple—it was found necessary to calibrate the couple from time to time. This was accomplished by determination of the melting points of zinc, silver and copper. The error of individual temperature observations does not exceed 5° below 1100° and 10° to 15° between 1100° and 1300°.

The carbon with which the porcelain tube was filled was crushed to pieces of a uniform size—about 5 mm on a side. Only the central portion of the tube (see Fig. 2) contained carbon, the remainder of the space being occupied by pieces of broken porcelain, which served at one end to heat the gas entering the tube, and at the other end, by reducing the size of the passage way, to increase the velocity of the gas through the region of falling temperature. Through the porcelain tube was passed a stream of CO_2 gas. In the earlier experiments CO_2 was prepared from marble and hydrochloric acid. Later, CO_2 was taken from a tank of liquid carbon dioxide.

The velocity of the gas over the carbon was determined by the dimensions of the tube, the weight and density of the carbon, and the temperature and the volume of gas passed through the tube per minute.[1]

The analyses were made by the Hempel method, both CO_2 and CO being absorbed. The amount of gas remaining in the burette after the absorption in cuprous chloride was seldom greater than two per cent.

V. EXPERIMENTS WITH CHARCOAL.

With the apparatus described in the preceding pages, experiments were conducted at temperatures ranging from 700° to 1300° C. The experiments with charcoal extended over a period of several months. The results are contained in tables 1-6.

TABLE 1

RATE OF FORMATION OF CO FROM CO_2 AND CHARCOAL

AT A TEMPERATURE OF 800° C.

$k_1 = 0.01968$
$k_2 = 3.031$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
∞	0	......	0.535
188.6	0.0053	0.503	0.534
115.9	0.0086	0.504	0.527
57.18	0.0175	0.518	0.508
45.70	0.0219	0.522	0.468
24.20	0.0413	0.375	0.345
15.50	0.0645	0.283	0.252
12.32	0.0810	0.245	0.209
2.686	0.354	0.063	0.051
1.550	0.645	0.039	0.030

[1] The increase in the volume of the gas in its passage through the reaction tube, due to the formation of two CO molecules in place of every molecule of CO_2 which disappears, makes it difficult to determine accurately the time of contact and consequently the velocity of the gas.

The values of t, the time of contact, given in the following tables are based on the volume of gas leaving the tube and are therefore somewhat too low. Since the major portion of the expansion takes place within a short distance from the entrance to the tube, the error here introduced is probably not appreciable.

TABLE 2

RATE OF FORMATION OF CO FROM CO_2 AND CHARCOAL AT A TEMPERATURE OF 850° C.

$k_1 = 0.07174$
$k_2 = 3.238$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
∞	0	......	0.742
123.0	0.0082	0.743	0.742
54.18	0.0184	0.702	0.741
24.43	0.0410	0.572	0.694
13.23	0.0756	0.526	0.564
9.268	0.1070	0.297	0.463
4.630	0.216	0.297	0.281
3.684	0.271	0.224	0.231
3.254	0.307	0.225	0.207

TABLE 3

RATE OF FORMATION OF CO FROM CO_2 AND CHARCOAL AT A TEMPERATURE OF 900° C.

$k_1 = 0.1540$

$k_2 = 2.599$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
∞	0	......	0.873
64.29	0.0156	0.873	0.873
44.18	0.0226	0.867	0.872
10.008	0.0999	0.708	0.739
4.257	0.234	0.498	0.472
2.840	0.352	0.311	0.351
2.172	0.461	0.344	0.284

TABLE 4

RATE OF FORMATION OF CO FROM CO_2 AND CHARCOAL

AT A TEMPERATURE OF 925° C.

$k_1 = 0.2175$

$k_2 = 2.298$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
∞	0	..... .	0.914
118.8	0.0084	0.947	0.914
81.2	0.0123	0.933	0.914
12.37	0.0807	0.848	0.875
5.80	0.1725	0.718	0.697
4.277	0.234	0.642	0.595
2.272	0.440	0.375	0.387

TABLE 5

RATE OF FORMATION OF CO FROM CO_2 AND CHARCOAL

AT A TEMPERATURE OF 1000° C.

$k_1 = 0.6404$

$k_2 = 4.708$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
∞	0	......	0.942
70.0	0.0143	0.949	0.942
18.60	0.0538	0.943	0.941
8.245	0.1195	0.903	0.938
3.675	0.272	0.797	0.869
2.296	0.436	0.795	0.752

TABLE 6

RATE OF FORMATION OF CO FROM CO_2 AND CHARCOAL

AT A TEMAERATURE OF 1100° C.

$k_1 = 1.495$
$k_2 = 5.275$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
∞	0	......	0.972
36.48	0.0274	0.987	0.972
10.43	0.0958	0.983	0.972
4.968	0.2010	0.981	0.971
3.640	0.2745	0.973	0.968
1.921	0.521	0.946	0.955

The first and second columns of each table give the time of contact t and the reciprocal of the time of contact $\frac{1}{t}$, which is equal to the velocity of the gas divided by the length of the charcoal column; thus

$$\frac{1}{t} = \frac{v}{l}.$$

The third column contains the percentages of CO observed, and the values in the last column were calculated by means of equation (13), viz:

$$x = \frac{4\ a}{a+1} \quad \frac{\gamma\ tanh\ \alpha t}{1+\gamma\ tanh\ \alpha t}$$

The method of computing α and γ of this equation is described in the appendix. The constants k_1 and k'_2 are determined by the relations,

$$k_1 = \frac{4a\gamma}{a+1}$$

$$k'_2 = \frac{\alpha(a+1)}{4\ \alpha\ \gamma} \ (1-\gamma^2)$$

Values of k_1, k_2, k'_2, α, and γ are given in table 7.

TABLE 7

CONSTANTS USED IN COMPUTATION OF x

Temp. C°	α $(a = 1)$	γ $(a = 1)$	k'_2	k_2	k_1	$K = \frac{k_1}{k_2}$
800.	0.0276	0.3568	0.03373	3.031	0.01968	0.006493
850.	0.0612	.5853	0.03443	3.238	0.07174	0.02216
900.	0.09998	.7711	0.02646	2.599	0.1540	0.05925
925	0.1297	.8388	0.02291	2.298	0.2175	0.09465
1000	0.3617	.8853	0.04416	4.708	0.6404	0.13603
1100	0.7921	.9437	0.04588	5.275	1.4950	0.28341

The calculated and observed values of x, the per cent of CO, agree within two or three per cent.

A comparison of the results in tables 1 to 6 shows in the first place that with increasing temperature there is a rapid increase in the percentage of CO obtained with any given rate of

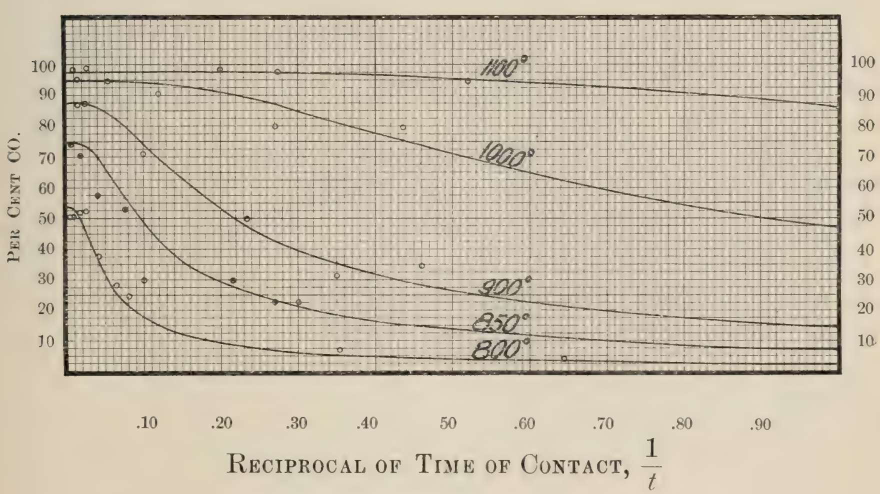


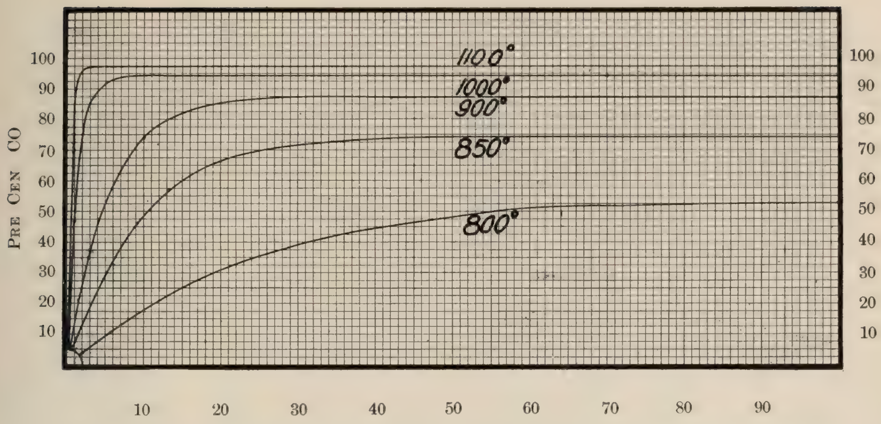
FIG. 4.

flow of the gas; in the second place that with increasing gas velocity at low temperatures the percentage of CO formed falls off very rapidly, at higher temperatures very slowly. These variations are illustrated by the curves in Fig. 4 in which the percentage of CO is plotted as a function of $\frac{1}{t} = \frac{v}{l}$. When l, the length of the charcoal column, is equal to one, i. e., is equal to the unit of length, then the numbers along the abscissa give the velocity of the gas in terms of the same unit of length, and per second. For example, the length of the charcoal column in the experiments here recorded, was approximately 20 cm. The velocity corresponding to the point $\frac{1}{t} = 1$ at the extreme right of Fig. 4, is therefore 20 cm. per second.

The general shape of all the curves in Fig. 4 is the same. The percentage of CO is greatest at zero velocity. With increasing values of $\frac{1}{t}$ each curve falls off, slowly at first then more rapidly, passing a point of inflection and finally becoming nearly horizontal. The intersections of the curves with the CO axis give the percentage of CO corresponding to the condition of equilibrium.

That a considerable amount of time is required to reach equilibrium in the reaction under consideration, is further illustrated in Fig. 5, in which the percentage of CO is plotted as a function of t, the time of contact. (One small division = 1 second). At 800° for example, the percentage of CO reaches a practically constant value at the end of 50 sec.; at 1000° in 6 sec.

The curves in Fig. 4 were plotted from values of x (= per cent CO) calculated from equation (13). The observed values are indicated by the small circles. By means of equation (13) it is possible to calculate the per cent of CO corresponding to any given gas velocity providing a and γ or k_1 and k_2 are known.



Time of Contact (Charcoal)

Fig. 5.

VI. Variations of K and k_1 With Temperature.

The values of k_1 and K given in table 7 exhibit a systematic variation with temperature. If equations can be found that will express k_1 and K as functions of the temperature it will then be possible to calculate the per cent of CO for any time of contact and any desired temperature. Such equations have been deduced by Van't Hoff from purely thermodynamical considerations. They are the following.[1]

$$\frac{d\,(ln\ K)}{dT} = -\frac{Q}{R\,T^2}, \tag{15}$$

and

$$\frac{d\,(\,ln\ k_1\,)}{dT} = \frac{A}{T^2} + B. \tag{16}$$

In these equations, Q is the latent heat of reaction at the absolute temperature T, A is a function of Q but is selected arbitrarily, and B is an arbitrary function of the temperature. By integration the latter equation becomes

---

[1] The symbol *ln* in the following equations stands for natural logarithm.

$$ln\ k_1 = -\frac{A}{T} + B\,T + C, \tag{17}$$

where C is an integration constant. The values of A, B, and C, in equation (5) have been determined from the simultaneous values of k_1 and T of tables 1-6. Table 8 contains the values of k_1, obtained at various temperatures as well as the values of k_1 calculated from equation (17). The agreement is remarkable good.

TABLE 8

VARIATION OF k_1 WITH TEMPERATURE (CHARCOAL)

$$ln\ k_1 = -\frac{50910}{T} - 0.0203\ T + 65.376$$

Temp. Deg. C.	Absolute Temp. T	k_1 (obs)	k_1 (calc)
800	1073	0.020	0.021
850	1123	0.073	0.064
900	1173	0.154	0.159
925	1198	0.217	0.237
1000	1273	0.640	0.629
1100	1373	1.490	1.53

In order to integrate the equation

$$\frac{d\,(ln\ K)}{d\,T} = -\frac{Q}{R\,T^2}$$

it is first necessary to determine the heat Q as a function of the temperature. It has been shown by Kirchoff that the increase of Q per degree rise in temperature is equal to the difference of the molecular heats of the factors and of the products of the reaction. Following this law, and taking the specific heat of a factor or product as a linear function of the temperature, which is very nearly true for gases, the relation between Q and T is given by the equation[1]

$$Q = Q_0 + c_1\,T + c_2\,T^2 \tag{18}$$

In this equation Q_0 denotes the heat of reaction for $T = 0$, and c_1 and c_2 are obtained as follows: Assuming that the mean specific heat of each gas is given by an expression of the form

[1] Haber, *Thermodynamics of Technical Gas Reactions*, p. 49, eq. (7a).

$$c = a + b\,T,$$

then c_1 is the difference between the sum of the a's of the factors and the sum of the a's of the products; likewise c_2 is the sum of the b's of the factors less the sum of the b's for the products. Substituting the value of Q given by (18) in (15) the result is

$$\frac{d(ln\ K)}{dt} = -\frac{1}{R}\left(\frac{Q_0}{T^2} + \frac{c_1}{T} + c_2\right)$$

whence by integration

$$ln\ K = \frac{1}{R}\left(\frac{Q_0}{T} - c_1\,ln\ T - c_2\,T\right) + C. \qquad (19)$$

The constants in this equation, (19), may be determined by either of two different methods: by experimental determinations of Q_0 c_1, and c_2, or from four or more simultaneous observations of K_{obs} and T. The first method was adopted in this instance, the following being the values of the quantities in question:

$$\begin{aligned} Q_0 &= -\ 40166 \\ c_1 &= -\ 2.055 \\ c_2 &= \quad 0.003104 \\ C &= \quad 8.604 \end{aligned}$$

In the determination of c_1 and c_2, Langen's values for the specific heats of CO and CO_2 and the value of Kunz for the specific heat of charcoal were employed.

The value of R (in gram-calories per deg.) is 1.985. Hence taking the above constants and this value of R, (19) reduces to

$$ln\,K = -\,\frac{20235}{T} + 1.035\,ln\,T - 0.001564\,T + 8.604. \qquad (20)$$

Table 9 gives values of K calculated from equation (20) along with values (marked K_{obs}) obtained from observed values of x and T in tables 1-6. In the fourth column are the observed values of x, the amount of CO in equilibrium with CO_2 and charcoal at temperatures from 800° to 1100°; and in the fifth columns the values of x corresponding to the values of K in the third column.

The constants of equation (19) were calculated also by the method of least squares, from simultaneous values of K_{obs} and T, but the agreement was less satisfactory than by the first method.

TABLE 9

VALUES OF K AND OF x_∞

Temp. C.	K (obs)	K (cal)	x_∞ (obs)	x_∞ (cal)	x_∞ (obs) Boudouard
500	......	0.000007	......	0.021	......
600	.....	0.00013	......	0.093	......
650	......	0.00046	......	0.185	0.39
700	......	0.00137	......	0.283	......
800	0.0065	0.0090	0.526	0.582	0.93
850	0.022	0.020	0.738	0.722	......
900	0.059	0.042	0.871	0.832	......
925	0.094	0.060	0.912	0.873	0.96
1000	0.136	0.151	0.939	0.945	......
1100	0.283	0.448	0.971	0.981	......
1200	......	1.120	......	0.994	......
1300	......	2.455	......	0.997	......
1400	......	4.826	......	0.9985	......
1500	......	8.671	......	0.9992	......
1600	......	14.44	......	0.9996	......

The agreement between "observed" and "calculated" values of K and k_1 in tables 8 and 9 shows that the changes of K and k_1, with temperature follow van't Hoff's laws. It is possible, therefore, by means of equations (17) and (19) and the values of the constants of these equations given in tables 8 and 9, to compute K and k_1 for any desired temperatures. Having the values of K and k_1 and consequently of k_2 $\left(k_2 = \frac{k_1}{K}\right)$ the per cent x of CO corresponding to any time of contact t can then be calculated by means of equation (13).

VII. EXPERIMENTS AT 700°.

In Fig. 4 the curve for 800° falls off very rapidly with increasing rate of flow of gas. At this temperature the gas velocity must be exceedingly low to obtain the equilibrium percentage of CO.

At temperatures below 800° it was practically impossible to reach equilibrium with a finite gas velocity. A great number of experiments were made at 700° but the results were too inconsistent to admit of mathematical treatment. Some of the observations are given in the following table:

TABLE 10

OBSERVATIONS AT 700°C. (CHARCOAL).

t = Time of contact in seconds	$\frac{1}{t}$	% CO/100
86.9	0.0115	0.012
86.2	0.0116	0.155
99.9	0.0100	0.077
23.4	0.0426	0.004
15.0	0.0668	0.014
7.11	0.1405	0.009
9.71	0.103	0.022
5.60	0.178	0.006
5.02	0.199	0.008
4.18	0.239	0.012

These results show that, except at exceedingly low velocities, the amount of CO formed was never greater than one or two per cent.

VIII. Experiments With Coke and Coal.

The experiments with coke and coal were conducted in the same manner as with charcoal. The material was crushed to pieces about 5 mm on a side. The constants α and γ of equation (13) were obtained for each temperature by the method given in the appendix. Tables 11-15 contain the results of the observations with coke. In the last column of each table are given the values of x, the percentage of CO formed, calculated from equation (13).

TABLE 11

RATE OF FORMATION OF CO FROM CO_2 AND COKE AT A TEMPERATURE OF 900° C.

$k_1 = 0.00231$

$k_2 = 0.03686$

Time of contact in seconds. t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
142.0	0.0070	0.276	0.278
80.20	0.0124	0.131	0.169
43.91	0.0228	0.094	0.096
24.82	0.0403	0.057	0.056
16.11	0.0620	0.049	0.037
9.575	0.1045	0.026	0.023
3.741	0.2671	0.008	0.009

TABLE 12

RATE OF FORMATION OF CO FROM CO_2 AND COKE AT A TEMPERATURE OF 1000° C.

$k_1 = 0.02323$

$k_2 = 0.3591$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
123.2	0.0081	0.784	0.866
80.25	0.0125	0.644	0.795
33.25	0.0301	0.529	0.527
18.72	0.0535	0.320	0.350
6.37	0.1571	0.139	0.138
4.101	0.2439	0.115	0.091
3.072	0.3258	0.092	0.069
1.983	0.5045	0.063	0.045

TABLE 13

RATE OF FORMATION OF CO FROM CO_2 AND COKE

AT A TEMPERATURE OF 1100° C.

$k_1 = 0.1335$
$k_2 = 0.5296$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
90.00	0.0111	0.971	0.971
29.92	0.0334	0.854	0.955
13.20	0.0758	0.661	0.817
6.765	0.1476	0.556	0.592
3.198	0.3135	0.317	0.346
1.784	0.5606	0.304	0.211
1.660	0.6030	0.240	0.1942
1 590	0.6299	0.221	0.190
1.462	0.6840	0.214	0.177
0.962	1.0399	0.133	0.121

TABLE 14

RATE OF FORMATION OF CO FROM CO_2 AND COKE

AT A TEMPERATURE OF 1200° C.

$k_1 = 0.4095$
$k_2 = 0.6718$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
18.92	0.0528	0.989	0.987
12.70	0.0788	0.978	0.983
8.250	0.1213	0.953	0.956
2.402	0.4160	0.685	0.624
1.582	0.6320	0.439	0.460
1.080	0.9260	0.335	0.357

TABLE 15

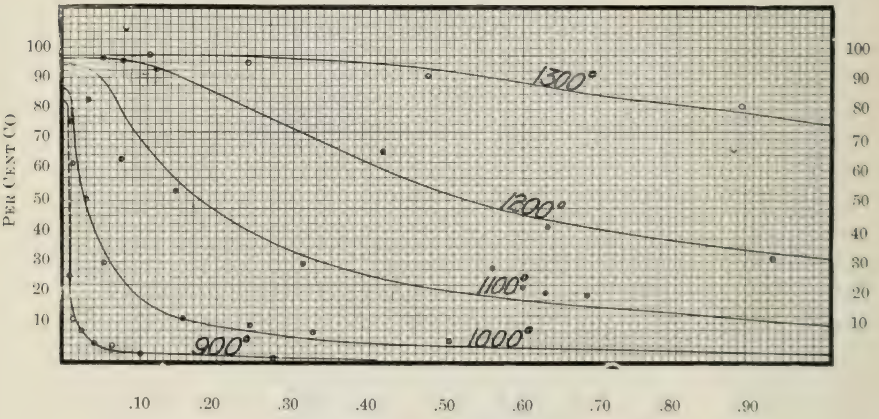
RATE OF FORMATION OF CO FROM CO_2 AND COKE

AT A TEMPERATURE OF 1300° C.

$k_1 = 1.483$
$k_2 = 0.7313$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
8.860	0.1129	0.999	0.997
4.149	0.2415	0.979	0.997
2.100	0.4760	0.932	0.955
1.130	0.8850	0.834	0.816

The results with coke are shown graphically in Fig. 6. The curves for 900°, 1000° and 1100° are considerably lower than the curves with charcoal for the same temperatures, except for very low velocities.



RECIPROCAL OF TIME OF CONTACT, $\frac{1}{t}$

FIG. 6.

TABLE 16

RATE OF FORMATION OF CO FROM CO_2 AND ANTHRACITE COAL AT A TEMPERATURE OF 1100° C.

$k_1 = 0.119$
$k_2 = 1.410$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
34.20	0.0293	0.8780	0.912
9.370	0.1069	0.6010	0.657
5.415	0.1848	0.4770	0.472
3.301	0.3026	0.3020	0.322
2.439	0.4101	0.2650	0.251

TABLE 17

RATE OF FORMATION OF CO FROM CO_2 AND ANTHRACITE COAL AT A TEMPERATURE OF 1200° C.

$k_1 = 0.2374$
$k_2 = 0.1767$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
47.05	0.0212	0.997	0.993
10.39	0.0964	0.856	0.901
5.070	0.1971	0.715	0.688
2.845	0.3516	0.423	0.472
1.592	0.6270	0.310	0.309

TABLE 18

RATE OF FORMATION OF CO FROM CO_2 AND ANTHRACITE COAL AT A TEMPERATURE OF 1300° C.

$k_1 = 0.5791$
$k_2 = 0.2016$

Time of contact in seconds t	$\frac{1}{t}$	% CO/100 Observed	% CO/100 Calculated
12.40	0.0806	0.999	0.997
6.030	0.1659	0.965	0.968
3.600	0.2779	0.824	0.876
2.980	0.3358	0.809	0.822
1.908	0.5249	0.663	0.668
1.070	0.9350	0.503	0.462

The observations with anthracite coal are given in tables 16, 17, and 18, and are illustrated graphically in Fig. 7.

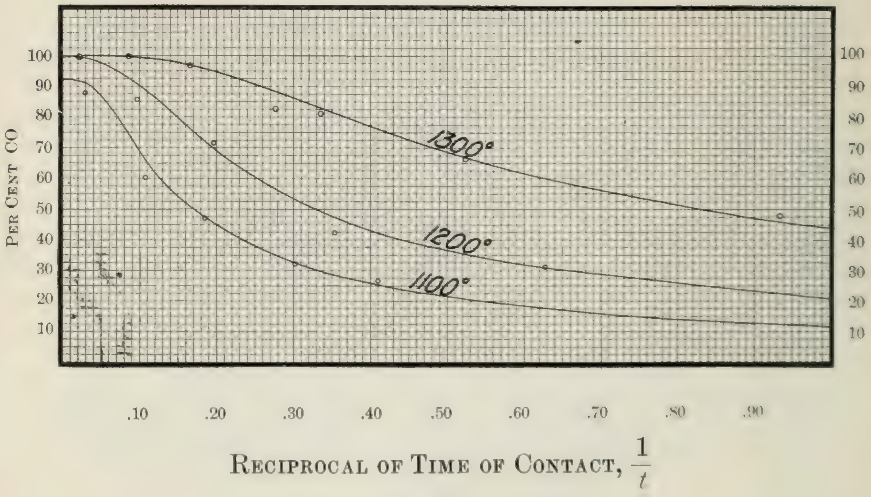


FIG. 7.

Here the curves fall off even more rapidly than the curves for coke in Fig. 6. With very low velocities, that is, when the time of contact is sufficient for the reaction to reach equilibrium, the percentage of CO formed is practically the same with each of the three forms of carbon. As the rate of flow of the gas increases, the effect of the difference in the reaction velocities becomes more appreciable.

TABLE 19

VALUES OF x_∞ FOR CHARCOAL, COKE, AND COAL.

Temp. C.	x_∞ (cal)	x_∞ (obs) Charcoal	x_∞ (obs) Coke	x_∞ (obs) Coal
900	0.832	0.871	0.875	......
1000	0.945	0.939	0.886	......
1100	0.981	0.971	0.968	0.914
1200	0.994	......	0.987	0.994
1300	0.997	......	0.996	0.997

Values of $x\,\infty$ the percentages of CO in equilibrium with CO_2, and charcoal, coke, and coal respectively, are given in table 19. The values in the second column of this table were calculated from the values of K in table 9, by means of the equation

$$\frac{x^2}{1 - x} = K\frac{RT}{p},$$

A comparison of Fig. 5, 6, and 7 shows that the reaction velocity is greatest with charcoal and lowest with anthracite coal. The temperature coefficient of k_1, the coefficient of reaction velocity, was determined for coal and coke in the same manner as for charcoal. The "observed" and "calculated" values of k_1 are shown in tables 20 and 21.

The constant k_2 in the equation

$$\frac{d[CO]}{dt} = k_1\,[CO_2] - k_2\,[CO]^2$$

is the coefficient of reaction velocity of the reaction

$$CO_2 + C = 2\,CO$$

taken from right to left. At the temperatures of these experiments, 800°-1300°, the carbon produced by the decomposition of

CO is in the form of lamp black, regardless of the form of carbon present in the reaction tube, viz: charcoal, coke, or coal. At any one temperature, therefore, k_2 should be the same in all three cases. From a comparison of tables 1-6, 11-15 and 16-18 it will be seen that there is considerable deviation in the values of k_2 for the three forms of carbon used. This is doubtless due in part to experimental errors. There is a further consideration, however, to which attention should be called, viz: that the reaction in question is not reversible. The lamp black produced by the reverse reaction

$$2\,CO = CO_2 + C,$$

is not identical physically with the form of carbon, charcoal, or coke that is consumed in the formation of CO. Consequently the law of chemical mass action is not strictly applicable. In the systems under consideration, equilibrium would not be reached until all the carbon has been transformed to lamp black.

TABLE 20

VARIATION OF k_1 WITH TEMPERATURE (COKE)

$$ln\ k_1 = -\frac{47220}{T} - 0.009699\ T + 45.597$$

Temp. C.	T	k_1 (obs)	k_1 (calc)
900	1173	0.0024	0.0023
1000	1273	0.021	0.023
1100	1373	0.121	0.134
1200	1473	0.473	0.410
1300	1573	1.38	1.48

TABLE 21

VARIATION OF k_1 WITH TEMPERATURE (ANTHRACITE COAL)

$$ln\ k_1 = \frac{31972}{T} + 0.02272\ T - 56.607$$

Temp. C.	T	k_1
1100	1373	0.119
1200	1473	0.237
1300	1573	0.579

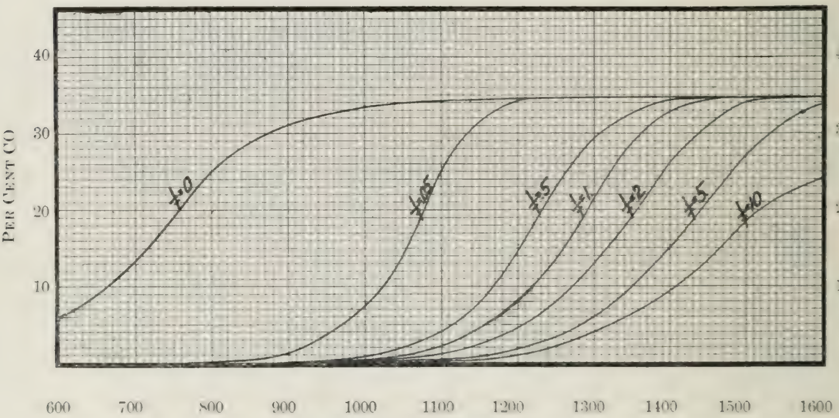
IX. APPLICATION OF EXPERIMENTAL RESULTS TO THE PROCESSES OF THE GAS PRODUCER AND BOILER FURNACE.

As stated in the introduction, the experiments here described were undertaken primarily to determine the temperature necessary for the formation of high percentage CO gas in the fuel bed of the gas producer, and to ascertain the conditions that govern the formation of CO in boiler furnaces. The results here presented indicate that the amount of CO formed in the gas producer depends on three factors: (1) the temperature; (2) the depth of the hot portion of the bed; and (3) the rate of flow of gas through the bed. Stated in a more concise form, the percentage of CO formed depends on the temperature and the time of contact of gas and carbon, i. e., the average time required for a molecule of gas to pass through the fuel bed. The variation of the percentage of CO with the rate of flow of gas is illustrated in Fig. 4, 6 and 7. The curves for coke, Fig. 6, may be taken as representing the conditions in the fuel bed of the producer. At 1300° C., for example, with zero velocity (time of contact $= \infty$) practically all the CO_2 will be converted to CO; when $\frac{1}{t} = 0.5$, (time of contact $t = 2$ sec.), 90 per cent CO is obtained; and when $t = 1$ only 80 per cent CO is formed. In a fuel bed one foot in depth, since

$$\frac{1}{t} = \frac{\textit{velocity of gas}}{\textit{depth of fuel bed}} = \frac{v}{l}$$

a time of contact of $t = 2$ sec. corresponds to a velocity 0.5 ft. per sec. and $t = 1$ to a velocity of 1 ft. per sec. At 1300° C., then, in a fuel bed one foot in depth, with a velocity of 0.5 ft. per sec. 90 per cent of CO would be formed and with a velocity of 1 ft. per sec. 80 per cent. In a fuel bed two feet in depth, the gas velocities corresponding to the same percentage of CO would be twice as great. In other words, for given conditions of temperature and quality of gas, the depth of bed and velocity of gas must vary proportionally and their ratio $\frac{v}{l}$ must remain constant. A fuel bed one foot in depth and a gas velocity of one foot per second should yield the same percentage of CO as a bed two feet in depth with a gas velocity of 2 ft. per sec.

It is impossible to determine accurately the velocity of the gas through the producer fuel bed, on account of the difficulty of estimating the magnitude of the passages through the bed.[1] The velocity lies probably between 0.5 and 5.0 ft. per sec. The right half of the curves in Fig. 6 lies within these limits and therefore corresponds approximately to the conditions of producer operation.



Temperature, Degrees C.

Fig. 8.

In Fig. 8 is shown graphically the variation with temperature of the amount of CO formed with different values of $\frac{1}{t}$. The ordinate is the per cent of CO in gas containing initially 21 per cent CO_2 (air in which the oxygen has been converted quantitatively to CO_2). The abscissa is temperature in degrees Centigrade. The upper curve, $\frac{1}{t} = 0$, represents the maximum amount of CO which could be produced from air. The intersection of the curve for any velocity with a given horizontal line, for example, the line for CO = 30 per cent, gives the temperature required to form that amount of CO with the particular velocity. Thus to obtain 30 per cent CO with a velocity of one foot per sec. (length of bed = 1 ft.) will require a temperature of 1360° C., and with a velocity of 2 ft. per sec., 1435°. The curves of Fig. 6 and 8 indicate that the temperature of the producer bed should not be less than 1300° C.

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[1] When any given number of pounds of air is passed per second through a fuel bed of given dimensions, the velocity through the bed will increase as the percentage of voids is decreased. Thus the velocity will be much higher with slack coal than with uniformly sized nut coal. Further, the per cent of voids will be influenced by the amount of coking and clinkering.

These investigations demonstrate that a very high temperature is necessary for the production of CO from CO_2 and carbon. There are other considerations, however, which are opposed to the operation of the fuel bed of the gas producer at extremely high temperature—above 1300° C.: A high temperature of fuel bed means that the gases will leave the producer at a high temperature and thus lower the efficiency of the producer. The gain in capacity will therefore be accompanied by a loss in efficiency, unless the heat of the gases can be used efficiently for generating steam and preheating the air blast. Also a high temperature favors clinkering. In the application of the results of these experiments to commercial producers and furnaces it will be necessary of course to consider the various questions that are involved.

Various explanations have been suggested to account for the presence of small amounts of carbon monoxide in the flue gases of boiler furnaces. Perhaps the one most generally accepted by engineers is that the oxygen of the air first unites with carbon to form CO_2 and that as this gas passes up through the hot fuel bed it combines with carbon in accordance with the equation

$$CO_2 + C = 2\,CO.$$

Assuming this to be the correct explanation, then the question to be solved is what conditions are favorable to this reaction and what conditions will tend to retard it. In the preceding paragraphs it has been shown that the higher the velocity of the gas and thinner the fuel bed, the less will be the percentage of CO formed. A heavy fuel bed in the boiler furnace would therefore favor the formation of CO. Also, the greater the supply of air to a given depth of bed, the less should be the tendency to form CO.

X SUMMARY AND CONCLUSIONS.

1. The rate of formation of CO in the reaction,

$$CO_2 + C = 2\,CO$$

has been determined with charcoal from 800° to 1100° C., with coke from 900° to 1300° C., and with anthracite coal from 1100° to 1300° C.

2. The differential equation for the velocity of incomplete reactions

$$\frac{dx}{dt} = k_1\left(a - \frac{a+1}{2}x\right) - k'_2 x^2$$

has been solved for given values of k'_2 and k_1, and it has been shown (in the appendix) that the method is applicable to other cases.

3. Van't Hoff's laws for the variation of equilibrium constants and coefficients of reaction velocity with temperature have been applied to the values of k_1 and K obtained in these experiments, and a close agreement between observed and calculated values has been found.

4. By means of the equations expressing the laws referred to in paragraphs (2) and (3) it is possible to compute the percentage of CO formed at any temperature and with any time of contact.

5. It has been shown that for the production of a high percentage of CO gas, the producer fuel bed should have a temperature of 1300° C. or over, and that increasing the depth of the hot

portion of the bed will increase the percentage of CO, and consequently the capacity of producer at first rapidly and then more and more slowly.

6. To minimize the production of CO in the boiler furnace the fuel bed should be thin. Increasing the velocity of the gas will tend to decrease rather than increase the percentage of CO formed.

APPENDIX

ON THE COMPUTATION OF THE CONSTANTS OF THE REACTION EQUATION

By Charles N. Haskins.

1. Reduction and Integration of the Differential Equation.

The differential equation is

$$\frac{dx}{dt} = k_1 \left(a - \frac{a+1}{2} x \right) - k_2 x^2,$$

where $100\, a = \%\ (CO + CO_2)$ at time $t = 0$, (1)

$100\, x = \%$ CO at time t,

$t =$ time in seconds,

and k_1 and k_2 are the two constants of the reaction the values of which are sought. The initial condition is that

$$x = 0, \text{ when } t = 0. \tag{2}$$

To integrate, we introduce a new variable z and new constants α, γ, defined by the relations

$$\left.\begin{aligned} z &= \frac{\left(\frac{a+1}{2}\right) x}{2a - \left(\frac{a+1}{2}\right) x}, & x &= \frac{2 a z}{\left(\frac{a+1}{2}\right)(1+z)}, \\ \alpha &= \frac{1}{2}\left(\frac{a+1}{2}\right) k_1 \sqrt{1 + \left(\frac{2}{a+1}\right)^2 \frac{4a\,k_2}{k_1}}, & k_1 &= \frac{2\,\alpha\,\gamma}{\left(\frac{a+1}{2}\right)}, \\ \gamma &= \frac{1}{\sqrt{1 + \left(\frac{2}{a+1}\right)^2 \frac{4ak_2}{k_1}}}, & k_2 &= \frac{1}{a}\left(\frac{a+1}{2}\right) \frac{\alpha\,(1 - \gamma^2)}{2\gamma} \end{aligned}\right\} \tag{3}$$

The differential equation becomes, under these substitutions,

$$\frac{dz}{dt} = \frac{a}{\gamma}(\gamma^2 - z^2) \tag{4}$$

with the initial condition $z = 0$, when $t = 0$. (5)

Integrating, we have

$$ln^1 \frac{\gamma + z}{\gamma - z} = 2\,at\ ; \tag{6}$$

and solving for z,

$$z = \gamma\,\frac{e^{at} - e^{-at}}{e^{at} + e^{-at}} = \gamma\ tanh\ at; \tag{7}$$

whence, substituting in (3),

$$x = \frac{2\ a\gamma\ tanh\ at}{\left(\frac{a+1}{2}\right)\left(1 + \gamma\ tanh\ at\right)}. \tag{8}$$

2. The Equation for γ and the Criterion for the Existence of One and Only One Root.

We have (equation 8) an expression by means of which the per cent of CO at any time t may be computed if the constants γ and a are known. We now wish to determine γ and a from two pairs of observed corresponding values of t and x. Let these two pairs be (t_1, x), and $(\ t_2\ x_2)$, and let $t_2 > t_1$.
Then since a is known we may compute

$$z_1 = \frac{\left(\frac{a+1}{2}\right) x_1}{2a - \left(\frac{a+1}{2}\right) x_1}, \qquad z_2 = \frac{\left(\frac{a+1}{2}\right) x_2}{2a - \left(\frac{a+1}{2}\right) x_2};$$

and have

$$ln\,\frac{\gamma + z_1}{\gamma - z_1} = 2\,at_1\ , \qquad ln\,\frac{\gamma + z_2}{\gamma - z_2} = 2\,at_2\,. \tag{9}$$

from which γ and a are to be determined. Eliminating a, we readily obtain

$$ln\,\frac{\gamma + z_2}{\gamma - z_2} = \frac{t_2}{t_1}\ ln\,\frac{\gamma + z_1}{\gamma - z_1}\ . \tag{10}$$

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[1] The symbols *ln x, log x* will be used to denote the natural and the common logarithm of *x*, respectively.

The determination of γ and α depends therefore on the solution of this (transcendental) equation in γ.

Consideration of the function

$$U(\gamma) \equiv t_1 \; ln \frac{\gamma + z_2}{\gamma - z_2} - t_2 \; ln \frac{\gamma + z_1}{\gamma - z_1}, \tag{11}$$

and of its derivative

$$U'(\gamma) \equiv -2\left(\frac{t_1 z_2}{\gamma^2 - z_2^2} - \frac{t_2 z_1}{\gamma^2 - z_1^2}\right) \tag{12}$$

shows that the equation

$$ln \frac{\gamma + z_2}{\gamma - z_2} = \frac{t_2}{t_1} \; ln \frac{\gamma + z_1}{\gamma - z_1} \tag{10}$$

has a root $\gamma > z_2$ when and only when

$$t_2 z_1 - t_1 z_2 > 0, \text{ that is, } \frac{z_2}{z_1} < \frac{t_2}{t_1}, \tag{13}$$

If a root exists there is but one, and it satisfies the inequalities

$$z_2 < \gamma < \sqrt{z_1 z_2 \frac{(t_2 z_2 - t_1 z_1)}{t_2 z_1 - t_1 z_2}}. \tag{14}$$

The inequality (13) furnishes a negative criterion for the applicability of the differential equation (1) to a reaction under investigation. For if the reaction is governed by equation (1) and if the observations are made with sufficient accuracy there must exist a γ satisfying equation (10) and hence the inequality (13) must be satisfied. If, then, this inequality is not satisfied, and hence no such γ can be found; then either the assumptions involved in (1) must be invalid, or there must be errors in the observations. On the other hand, if (13) is satisfied we can only conclude that (1) *may* be applicable, and we proceed to determine whether it is so by computing γ and α and comparing the values of x computed by means of (8) with the observed values of x.

3. SOLUTION OF THE EQUATION $ln \frac{\gamma + z_2}{\gamma - z_2} = \frac{t_2}{t_1} ln \frac{\gamma + z_1}{\gamma - z_1}$.

If the selected pairs (t_1, x_1), (t_2, x_2) of observed values satisfy the criterion

$$\frac{z_2}{z_1} < \frac{t_2}{t_1} \tag{13}$$

we compute γ as follows. Passing, for convenience of computation, from natural to common logarithms, we have

$$log \frac{\gamma + z_2}{\gamma - z_2} = \frac{t_2}{t_1} log \frac{\gamma + z_1}{\gamma - z_1}. \tag{10a}$$

Assume now a value for γ, say $\gamma = \gamma_1$,

where $$z_2 < \gamma_1 < \sqrt{z_1 z_2 \frac{(t_2 z_2 - t_1 z_1)}{t_2 z_1 - t_1 z_2}}.$$

Then we may compute a quantity $log X_1$ by the equation

$$log X_1 = \frac{t_2}{t_1} log \frac{\gamma + z_1}{\gamma - z_1}, \tag{15}$$

Determine now a new value of γ, $\gamma = \gamma_2$, by the relation

$$log \frac{\gamma_2 + z_2}{\gamma_2 - z_2} = log X_1 \tag{16}$$

that is,

$$\frac{\gamma_2 + z_2}{\gamma_2 - x_2} = X_1 \tag{16a}$$

or[1]

$$\gamma_2 = z_2 \frac{X_1 + 1}{X_1 - 1} \tag{16b}$$

Proceed now to determine a new approximation γ_3 from γ_2 in the same way that γ_2 was determined from γ_1, and continue the process until its repetition produces either no change, or a change which is negligible compared with the experimental errors. It will be found that in general the process converges fairly rapidly and only a few repetitions are necessary.

---

[1] This computation may be abridged by the use of Gaussian logarithms.

Suppose, then, that γ has been found by this process. Then α is computed by either of the relations

$$2\,\alpha = \frac{1}{t_2}\,ln\,\frac{\gamma + z_1}{\gamma - z_1},\quad 2\,\alpha = \frac{1}{t_1}\,ln\,\frac{\gamma + z_2}{\gamma - z_2} \tag{9a}$$

or, what amounts to the same thing, if N is the last of the numbers $N_1\ N_2, \ldots$ used in computing γ,

$$\begin{gathered} 2\,\alpha = \frac{1}{t_2}\,ln\,\frac{\gamma + z_2}{\gamma - z_2} = \frac{1}{t_2}\,ln\,N = \frac{1}{t_2}\,log\,N \cdot ln\,10, \\ 2\,\alpha = \frac{2.3026}{t_2}\,log\,N. \end{gathered} \tag{17}$$

4. COMPUTATION OF THE REACTION-CONSTANTS k_1, k_2, AND VERIFICATION OF THE REACTION-EQUATION.

When the constants α, γ have been computed we can find the original constants k_1, k_2 by the relations

$$k_1 = \frac{2\,\alpha\gamma}{\left(\frac{a+1}{2}\right)},\qquad k_2 = \frac{1}{a}\left(\frac{a+1}{2}\right)\frac{\alpha\,(1-\gamma^2)}{\gamma}. \tag{3}$$

To determine the applicability of the reaction-equation (1) to the case in hand, we have now only to introduce the values α, γ, just found into the equation

$$z = \gamma\,tanh\,\alpha t, \tag{7}$$

$$x = \frac{2\,a\,\gamma\,tanh\,\alpha t}{\left(\frac{a+1}{2}\right)\left(1 + \gamma\,tanh\,\alpha t\right)} \tag{8}$$

and compare the values of z or x obtained with those found by observation. For this purpose equation (7) is the simpler, especially when the z's corresponding to observed values of x have already been computed.

5. CORRECTION OF THE CONSTANTS α, γ BY THE METHOD OF LEAST SQUARES.

The constants α, γ obtained above are determined by two pairs of observations only. It is of course desirable that all the observations be used in fixing their values, as on account of experimental errors the values obtained from different pairs of observations will in general not be identical. We proceed, therefore, to correct the constants by the Method of Least Squares.

Let $(t_1, x_1);(t_2, x_2);\ldots(t_n, x_n)$ be n observed pairs of values of t and x. The problem is then to determine α and γ in such a way that if

$$ln\left(\frac{\gamma + z_i}{\gamma - z_i}\right) - 2\,\alpha\,t_i \equiv \delta_i \tag{6^1}$$

then

$$n\delta^2 \equiv \sum_1^n{}_i\,\delta_i^2 \tag{18}$$

shall be a minimum.

In order that α and γ shall make $n\delta^2$ a minimum they must satisfy the so-called normal equations:

$$\begin{aligned}
&\frac{n}{2}\frac{d(\delta^2)}{d\alpha} \equiv \sum_1^n{}_i\,\delta_i\frac{d\delta_i}{d\alpha} \equiv \sum_1^n{}_i\;2\,t_i\left\{2\,\alpha\,t_i - ln\left(\frac{\gamma + z_i}{\gamma - z_i}\right)\right\} = 0\,,\\
&\frac{n}{2}\frac{d(\delta^2)}{d\gamma} \equiv \sum_1^n{}_i\,\delta_i\frac{d\delta_i}{d\gamma} \equiv\\
&\qquad \sum_1^n{}_i\left\{\frac{1}{\gamma + z_i} - \frac{1}{\gamma - z_i}\right\}\left\{ln\left(\frac{\gamma + z_i}{\gamma - z_i}\right) - 2\,\alpha t_i\right\} = 0\,.
\end{aligned} \tag{19}$$

These equations may be written

$$\begin{aligned}
&2\,\alpha\sum_1^n{}_i\,t_i^2 + \sum_1^n{}_i\,t_i\,ln\left(\frac{\gamma - z_i}{\gamma + z_i}\right) = 0\,,\\
&2\,\alpha\sum_1^n{}_i\,\frac{t_i\,z_i}{\gamma^2 - z_i^2} + \sum_1^n{}_i\,\frac{z_i}{\gamma^2 - z_i^2}\,ln\left(\frac{\gamma - z_i}{\gamma + z_i}\right) = 0\,.
\end{aligned} \tag{20}$$

As their exact solution in their present form is impracticable on account of their complexity we replace them in the usual way by a system of approximately equivalent linear equations, by making use of the fact that the quantities u, v by which a and γ differ from a_0, γ_0 respectively are small compared with a_0, γ_0.

Substituting

$$\begin{aligned} a &= a_0 + u \\ \gamma &= \gamma_0 + v, \end{aligned} \tag{21}$$

we have

$$2u\sum_1^n{}^i\, t_i^2 + \sum_1^n{}^i\, t_i\, ln\left(\frac{1+\dfrac{v}{\gamma_0 - z_i}}{1+\dfrac{v}{\gamma_0 + z_i}}\right) = \sum_1^n{}^i\, t_i\left\{ln\left(\frac{\gamma_0 + z_i}{\gamma_0 - z_i}\right) - 2at_i\right\}$$

$$2u\sum_1^n{}^i \frac{t_i\, z_i}{\left(\gamma_0^2 - z_i^2\right)\left(1+\dfrac{2\gamma_0 v + v^2}{\gamma_0^2 - z_i^2}\right)} + \sum_1^n{}^i \frac{z_i\, ln\left(\dfrac{1+\dfrac{v}{\gamma_0 - z_i}}{1+\dfrac{v}{\gamma_0 + z_i}}\right)}{\left(\gamma_0^2 - z_i^2\right)\left(1+\dfrac{2\gamma_0 v + v^2}{\gamma_0^2 - z_i^2}\right)} \tag{22}$$

$$= \sum_1^n{}^i \frac{z_i\left\{ln\left(\dfrac{\gamma_0 + z_i}{\gamma_0 - z_i}\right) - 2a_0 t_i\right\}}{\left(\gamma_0^2 - z_i^2\right)\left(1+\dfrac{2\gamma_0 v + v^2}{\gamma_0^2 - z_i^2}\right)}.$$

Expanding the logarithms by Maclaurin's series and neglecting terms of the order of uv and v^2 in comparison with those of the order of u and v we have

$$\begin{aligned} u\sum_1^n{}^i\, t_i^2 + v\sum_1^n{}^i \frac{t_i\, z_i}{\gamma_0^2 - z_i^2} &= \sum_1^n{}^i \frac{t_i}{2}\left(ln\frac{\gamma_0 + z_i}{\gamma_0 - z_i} - 2a_0 t_i\right) \\ u\sum_1^n{}^i \frac{t_i\, z_i}{\gamma_0^2 - z_i^2} + v\sum_1^n{}^i \frac{z_i^2}{(\gamma_0^2 - z_i^2)} &= \sum_1^n{}^i \frac{z_i}{(\gamma_0^2 - z_i^2)}\left(ln\frac{\gamma_0 + z_i}{\gamma_0 - z_i} - 2a_0 t_i\right) \end{aligned} \tag{23}$$

Expressing the natural logarithms in terms of common logarithms we have, putting

$$A_i \equiv t_i \ , \quad B_i \equiv \frac{z_i}{\gamma_0^2 - z_i^2} \ , \quad C_i \equiv log \frac{\gamma_0 + z_i}{\gamma_0 - z_i} - M t_i \ ,$$

$$K \equiv \frac{ln \ 10}{2} \equiv 1.15129 \ , \quad M \equiv \frac{2a_0}{ln \ 10} \equiv 0.86859 \ a_0 \ ;$$

$$u \sum_1^n {}_i \ A_i^2 + v \sum_1^n {}_i \ A_i \ B_i = K \sum_1^n {}_i \ A_i \ C_i \ , \tag{24}$$

$$u \sum_1^n {}_i \ B_i \ A_i + v \sum_1^n {}_i \ B^2{}_i = K \sum_1^n {}_i \ B_i \ C_i \ , \tag{25}$$

or in the usual notation of the method of least squares

$$\begin{aligned} u \, [A \, A] + v \, [A \, B] &= K \, [A \, C], \\ u \, [B \, A] + v [B \, B] &= K \, [B \, C]. \end{aligned} \tag{26}$$

From these equations u and v are readily computed and hence the corrected values

$$\begin{aligned} \gamma &= a_0 + u \\ \gamma &= a_0 + v \end{aligned} \tag{21}$$

are found.

6. APPLICATION OF THE METHOD OF §§ 3, 4 TO OTHER EQUATIONS OF REACTION-VELOCITY.

The well known equation[1]

$$\frac{dx}{dt} = k_1 \, (1 - x \,)^2 - k_2 \, x^2 \ , \tag{27}$$

with the initial condition $x = 0$, when $t = 0$, is reducible by the substitutions

$$\left.\begin{aligned} z &= \frac{x}{1 - x} \ , & x &= \frac{z}{1 + z} \ , \\ a &= \sqrt{k_1 \, k_2} \ , & k_1 &= a \, \gamma \ , \\ \gamma &= \sqrt{\frac{k_1}{k_2}} \ , & k_2 &= \frac{a}{\gamma} \ , \end{aligned}\right\} \tag{28}$$

to the form we have considered, viz.:

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[1] Cf Nernst, *Theoretische Chemie*, 5 Aufl, p. 564; 2d English edition, p. 568.

$$\frac{dz}{dt} = \frac{a}{\gamma}(\gamma^2 - z^2) \qquad (4)$$

with the initial condition $z = 0$ when $t = 0$. Its integral is, therefore,

$$ln \frac{\gamma + z}{\gamma - z} = 2 at , \qquad (6)$$

or

$$z = \gamma \ tanh \ at, \qquad (7)$$

or

$$x = \frac{\gamma \ tanh \ at}{1 + \gamma \ tanh \ at} , \qquad (8)$$

and the constants are determined by the equation

$$ln \frac{\gamma + z_2}{\gamma - z_2} = \frac{t_2}{t_1} \ ln \frac{\gamma + z_1}{\gamma - z_1} \qquad (10)$$

if the criterion

$$\frac{z_2}{z_1} < \frac{t_2}{t_1} \qquad (13)$$

is satisfied.

The more general equation[1]

$$\frac{dx}{dt} = k_1 (a_1 - x) (b_1 - x) - k_2 (a_2 + x) (b_2 + x), \qquad (29)$$

with initial conditions $x = 0$, when $t = 0$ is reducible by a substitution of the form

$$x = \frac{\rho z - \sigma}{1 + z}. \qquad (30)$$

where ρ and σ are constants depending on a_1, b_1, a_2, b_2 *but not on* k_1, k_2, to the equation

$$\frac{dz}{dt} = \frac{a}{\gamma}(\gamma^2 - z^2). \qquad (4)$$

The initial conditions, however, are now not

$$t = 0, \ z = 0, \qquad (5)$$

but

$$t = 0, \ z = \frac{\sigma}{\rho} \equiv z_0 \ ; \qquad (5')$$

and hence the integral and the equation determining the constants are more complicated.

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[1] Cf. Nernst, *Theoretische Chemie*, 5 Aufl. p. 543; 2d English edition, p. 542.

The equation determining γ is

$$ln \frac{\gamma + z_2}{\gamma - z_2} = \frac{t_2}{t_1} ln \frac{\gamma + z_1}{\gamma - z_1} - \left(\frac{t_2}{t_1} - 1 \right) ln \frac{\gamma + z_0}{\gamma - z_0} \tag{31}$$

and the criterion for the existence of a solution is

$$t_2 z_1 - t_1 z_2 - (t_2 - t_1) z_0 > 0. \tag{32}$$

The solution, if existent, is unique, and is determined by process similar to that of § 3.

7. Conclusion.

The analysis in the preceding sections furnishes a simple negative criterion (13) or (32) for the applicability of the differential equation (1) or (29) to a given reaction and, in case this criterion is satisfied, provides a straightforward method of computing the numerical values of the reaction constants k_1 and k_2 from *any* two pairs of observed corresponding values of x and t. It renders unnecessary, moreover, except as a matter of control, any observations of equilibrium conditions.

The detailed discussion of the more general equation (29) is reserved for subsequent publication.

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FUEL TESTS WITH HOUSE-HEATING BOILERS

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GENERAL INTRODUCTION

This bulletin describes one hundred thirty fuel tests with house-heating boilers. For convenience, it has been divided into three parts.

Part I describes 48 tests made by the Engineering Experiment Station of the University of Illinois, when burning the various kinds of fuel commonly used in house-heating work in the state of Illinois.

Part II relates to 58 tests made under the direction of the United States Geological Survey at St. Louis, Missouri. Of these tests, 47 were upon briquetted fuel, and 11 upon raw coal.

Part III describes 24 tests made by the Engineering Experiment Station of the University of Illinois, using briquetted fuel.

All these tests were conducted under conditions which differed considerably, and by methods differing more or less in detail. The tests made by the Engineering Experiment Station at the University of Illinois extend over a considerable length of time and have been carried on by regular members of the fuel test division, occasional changes in the personnel having been required. The observations on the tests made at St. Louis were all made by one observer. For these reasons, therefore, the results are hardly comparable, except in a more or less general way, and little attempt has been made to make such comparisons.

The descriptive matter and discussion included in each part apply to its own series of tests, unless otherwise stated. Most of this descriptive matter and discussion has been incorporated in connection with the tests of Part I. Part II and Part III are for the most part a compilation of data and results of the tests considered. The tests made at St. Louis under the supervision of the United States Geological Survey are reported and discussed in Bulletin 366 issued by that department. The Engineering Experiment Station is under obligation to the United States Geological Survey for the information concerning the St. Louis tests here published.

I. FUEL TESTS WITH HOUSE-HEATING BOILERS MADE BY THE ENGINEERING EXPERIMENT STATION

(48 tests with representative fuels)

1. *Introduction*

The purpose of these tests was in general two-fold. First, to obtain the information usually obtained from boiler trials when operating upon house-heating boilers with various types of fuel commonly used for domestic purposes, in order that comparison might readily be made; second, to obtain information that might assist in developing satisfactory methods for conducting house-heating boiler trials whether the object of the test be to test the fuel, the equipment, or the two combined.

Some of the more important deductions drawn have been summarized in the paragraphs immediately following. The data and discussion relative to these deductions will be found in subsequent portions of the bulletin. The conclusions regarding methods for conducting house-heating boiler trials, having been drawn from one series of tests during which most of the important conditions were maintained constant, they can be considered as of only a preliminary nature. Further tests, under varying conditions, will, it is hoped, furnish further information in this connection. It was deemed advisable to present the information relative to the tests as fuel tests at this time together with such suggestions as could be made in regard to methods for conducting such tests.

2. *Summary of Conclusions*

A. Efficiency and Fuel Cost

(*1*). *The evaporative efficiencies* of house-heating boilers vary greatly with changes in other conditions and extreme care should be used in making comparisons.

(*2*). *The efficiencies* for the tests under consideration varied from 44% to 66%; thus covering about the same range or a somewhat lower range than is found in power boiler work.

(*3*). *A still wider range* of efficiencies will exist under the variable capacity conditions common to average residence heating work.

(*4*). *The range in efficiencies* found was due principally to the different kinds of fuel tested.

(*5*). *Fuels high in fixed carbon content*, such as anthracite and coke, give relatively high efficiencies as compared with fuels low in fixed carbon content.

(*6*). *Present methods of burning and present types of boilers* are particularly well adapted to burning anthracite and other coals high in carbon content.

(*7*). *Coke burning* presents special problems as to methods of burning and construction of equipment.

(*8*). *A high fixed carbon* content as opposed to a high volatile content is desirable in a fuel for domestic purposes.

(*9*). *The low efficiencies* with fuel of high volatile content, such as the Illinois coal, indicate the necessity of improvement as to equipment and methods of burning in order that this fuel may be placed more nearly on an equal footing with other fuels in this respect when employed for house-heating purposes.

(*10*). *Variations in efficiencies*, apparently due to slight changes in fire and other conditions indicate the possibility of obtaining higher efficiencies in many cases by careful attention to details relating to fuel, operation and equipment.

(*11*). *Illinois coal* may be obtained at from $\frac{1}{4}$ to $\frac{1}{2}$ of the cost per ton of anthracite. The cost per British thermal unit will be relatively slightly higher for Illinois coal than when expressed as cost per ton. Roughly, however, 10,000 B. t. u. can be purchased in Illinois coal at from $\frac{1}{4}$ to $\frac{1}{2}$ of the cost in anthracite.

(*12*). *Illinois coal* is considerably cheaper, expressed both as cost per ton and as cost per British thermal unit than Pocahontas coal or coke.

(*13*). *Fixed carbon* can be bought much more cheaply in the form of coke than as anthracite, and at as low or lower a price than it can be purchased in Pocahontas or Illinois coal.

(*14*). *With Illinois coal* as fuel, water can be evaporated in house-heating boilers at about 50% of the fuel cost of anthracite and about 75% of the fuel cost of Pocahontas coal or coke.

(*15*). *The relatively low cost* of Illinois coal especially as compared with the eastern coals will insure its continued use for domestic purposes. The amount of this fuel used for such purposes will probably increase in spite of the disadvantages at present connected with its burning. This condition emphasizes the necessity for improvement in the methods of burning the cheaper fuel.

(*16*). *The low fuel cost* of evaporation for Illinois coal as compared with coke is considerable and will insure the continued use of the raw coal until prices of the two fuels are more nearly equal. Improvement in methods of burning and equipment are needed for burning each of these fuels and such improvements will, doubtless, affect the relative quantity of each which is used.

(*17*). *Improvements* tending toward a reduction of smoke, dirt or other disadvantages connected with the burning of the cheaper coal will, doubtless, also increase the efficiency with which that fuel may be used and make the fuel cost differences still more favorable to the cheaper fuel.

(*18*). *Based upon present prices* of Illinois coal and considering evaporative performance only, anthracite, for instance, is worth only from $3.00 to $4.00 per ton. The additional amount which is paid for it must be considered as expended for advantages possessed by the anthracite, such as cleanliness and ease of fire control, which are not possessed by the other fuel.

B. Cleanliness, Control, Attendance

(*19*). *Anthracite and Pocahontas* coal are particularly well adapted to maintaining uniform pressure and fire conditions over a long period of time with little attention. The quick-burning Illinois coals are much less reliable in this respect.

(*20*). *Satisfactory regulation* is more readily accomplished with the eastern fuels and with coke than with the Illinois coal.

(*21*). *The total attendance* required may be considerably less when burning anthracite than the other fuels. The same may be said in general as between coke and Pocahontas as compared with the Illinois coal. This condition would be especially noticeable in connection with heating apparatus used in residence work.

(*22*). *Anthracite and coke* possess marked advantages over the other fuels, especially over the Illinois coal, with respect to cleanliness. They are in general cleaner in and about the boiler room and do not smoke, either from the chimney or in the boiler room. Little trouble is had with soot or ash in the flues and with reasonable care noxious gases should not be given off in the furnace room; also, the ash is small in amount and easily handled.

Clinkering may take place to some extent.

(*23*). *Pocahontas coal* is less clean to handle than anthracite or coke, makes some smoke, soot and other dirt and burns with a small amount of very easily handled ash which is not apt to clinker.

(*24*). *Illinois coal*, comparatively speaking, smokes badly, deposits a large amount of soot in the flues, may cause the emission of smoke and noxious gases into the boiler room. It is dirty to handle in and about the boiler room. The amount and performance of the ash in the fire-box vary considerably with different kinds of Illinois coal. In general, however, the ash is considerable in amount and clinkers to a greater or less extent, sometimes badly.

(*25*). *Washing and sizing Illinois coal* eliminate to a very considerable extent the objectionable features with regard to smoke, soot, dirt and ash just mentioned.

C. General

(*26*). *In considering house-heating boiler tests*, a number of important considerations, such as efficiency, fuel cost, attendance, control, cleanliness and equipment must be taken into account. The relative importance of such factors can not be stated definitely and varies greatly with the nature of the service required of any given installation.

(*27*). *Efficiency and fuel cost* may become the items of greatest importance where heating work is upon a comparatively large scale approaching power boiler conditions.

(*28*). *Simplicity and the ease* with which the heating apparatus can be cared for may be of greater importance than high evaporative efficiency.

(*29*). *The condition which requires the minimum amount of attendance* may be the most satisfactory and economical and more than offset the consumption of some extra fuel.

(*30*). *The ability to get up steam quickly*, and to maintain uniform pressure and fire conditions over comparatively long periods of time may be of greater importance than questions relating to either fuel or equipment.

(*31*). *The desire or necessity for cleanliness* with respect to smoke, soot, ash and dust or dirt in the boiler room, may warrant the use of high priced fuel.

D. *Method of Conducting Tests*

(*32*). *In general* the test should be made under conditions approximating those of the service which is required of the fuel and equipment. To do this will require tests of two kinds.

(*a*) *If the load demand is fairly constant and comparatively high*, test at the required load in a manner generally similar to that employed in power boiler work, making evaporative performance the main item sought.

(*b*) *If the load demand is very variable*, test under conditions approximately similar to operating conditions. In such tests questions relating to attendance, cleanliness and control will generally be found of equal or greater importance than those relating to efficiency and the tests should be so conducted as to give the fullest information possible along these lines.

(*33*). *Make the tests* classified under (*a*) of paragraph 32 at least 16 hours long and to consist of at least three firing charges of fuel.

(*34*). *Make the tests* classified under (*b*) paragraph 32, 24 hours long.

(*35*). *Use the standard method* for starting and stopping all tests, that is, start the test with a fresh fire and close it by drawing the fire and allowing for the residue of unconsumed fuel thus obtained.

(*36*). *No conclusions are offered* as to the best method of conducting tests for the purpose of determining the proper rating to be given to particular apparatus. Further tests to be reported upon later will, it is hoped, be of service in this connection.

3. *General Discussion of the Problem Relating to Tests of Fuel in House-heating Boilers*

(*1*). To determine the relative value of a fuel for different purposes or of different fuels for a given purpose, it generally seems advisable to make the tests in connection with the apparatus with which the fuels would ordinarily be employed, and under conditions at least approximately similar to those of every day practice. Laboratory methods, such as chemical analysis and calorific determination, are in general considered as only a part of a fuel test and are employed along with other data in interpreting the results. We thus have fuel tests made in connection with boilers, gas producers, coking ovens, furnaces, and other devices in order that the results and deductions may be applicable to the particular problem in hand. In any given branch of fuel testing this process of applying particular conditions may be carried still further.

(*2*). *Small heating units as compared with large units.*—The fuel tests here considered were made in connection with house-heating boilers of comparatively small size. On account of the small amount of available information relative to a satisfactory method for conducting house-heating boiler tests, one of the principal purposes in conducting these tests was to obtain information that would assist in developing such a method. Fuel tests with house-heating boilers will of necessity be similar, in many respects, to the tests made in connection with power boilers. While not overlooking the difference which must exist, due to the unlike conditions under which these two types of boilers operate, and the purposes for which each type is operated, it was deemed advisable as a first step in this work to make a series of tests upon house-heating boilers as nearly as possible by the methods which have been found satisfactory when testing with power boilers.

In work with the large units, fuel cost is generally the important factor, and the highest evaporative performance that can be obtained per dollar expended for fuel is the condition desired. Conditions relating to attendance, equipment, cleanliness and methods of operation are of secondary importance, and are capable of considerable variation or adjustment (depending upon the size and importance of the installation) in order to obtain a high rate of evaporation. Conditions surrounding house-heating boilers are, however, of such a nature that they can not be readily changed. Higher rates of evaporation and more efficient rates of combustion could, doubtless, often be obtained by having a fireman in constant attendance. The cost of such attendance is, however, in most cases prohibitive. The use of unusually expensive, complicated, or large apparatus is from the nature of the service undesirable. Conditions relating to equipment and attendance may be of so much greater relative importance than low cost of evaporation as to permit of relatively inefficient performance in order to satisfy those considerations. In many instances it will be found that the condition which requires the minimum amount of attendance is the condition which is most satisfactory and the advantage of simple, easily cared for equipment will more than offset the consumption of some extra fuel. It may be of much greater importance to get steam up quickly, or otherwise produce the desired heating effect quickly, and to be able to maintain a uniform rate of heat generation through a considerable length of time, than it is to furnish that heat at the lowest possible fuel cost. Such considerations may warrant the use of high-priced fuels or the sacrifice of evaporative efficiency for the sake of ease of fire control. Regulation, ease with which good fire conditions are maintained with respect to ash and clinker, the tendency of flues to become fouled, dirt in the form of dust, smoke, soot, or ash, whether from the coal pile, the fire-box, or chimney, are all important considerations aside from their relation to evaporative performance.

(*3*). *Outline.*—In order that the results of house-heating boiler tests may be of the greatest use, it becomes desirable to report more or less fully upon quite a number of conditions. The following outline presents most of the questions which will arise in making fuel tests with house-heating boilers.

Efficiency
- (*a*) Evaporative performance, including efficiencies of the boiler and furnace, grate, and of the plant.
- (*b*) Fuel cost for heat delivered.

Control
- (*a*) Time required to get up steam pressure.
- (*b*) Length of time of holding uniform pressure and satisfactory fire conditions without attention.
- (*c*) Uniformity of regulation.
- (*d*) Total attendance.
- (*e*) Capacity.

Cleanliness
- (*a*) Dust and dirt in boiler room.
- (*b*) Ash and clinkers.
- (*c*) Soot and ash in flue.
- (*d*) Smoke.
- (*e*) Smoke and gases in furnace room.

(*4*). *Relative importance of conditions.*—It is obviously impossible to measure exactly just what is the relative importance of the factors as above grouped under control and cleanliness, as compared with boiler efficiency and evaporative performance, but it is evident that they are of much greater relative importance when considering house-heating boilers than when considering power boilers. It is also true that the importance of certain factors will vary greatly according to the service rendered. In heating large school buildings with house-heating boilers the conditions may approximate very closely conditions in power work, and evaporative performance will be the item of greatest importance, while in the case of heating a small residence, cleanliness and ease of control may readily seem to be of first importance.

(*5*). *Capacity*.—The problem or problems in connection with each of the items mentioned are probably evident, with the possible exception of the item *capacity* which is listed under the head of control. In the case of a house-heating boiler, the question relative to capacity which is of importance, is how many square feet of radiation can be served by the boiler through comparatively long periods of time without attention, except at the time of firing. It is generally desired to know how many square feet of radiation can be served through a period of from six to eight hours without attention during that time. The same amount of fuel consumed within a short time should serve more radiating surface per hour than when burned during a longer period of time. The one hour period as employed in defining a horse-power, and as used in rating power boilers, is not satisfactory for comparative purposes in connection with house-heating boiler work. In this kind of work, then, in order that information relative to capacity may have the greatest usefulness, it should be based upon the evaporation which can be obtained during a period of from six to eight hours without attention, rather than upon the evaporation obtained in one hour with whatever attendance may be required. Thus a boiler rated at 1000 square feet should be capable of serving that amount of radiation without attention for a much longer time than one hour. In order to give satisfaction as a house-heating boiler, it should probably be able to serve that radiation for a period of at least six hours without attention during that time.

(*6*). *Purpose of tests.*—In carrying on the tests herein reported it soon became evident that it would be difficult to conduct tests so that suitable data concerning all of the above mentioned items could be obtained from any one test. Tests so run that the data would be of the greatest comparative value, for instance, in the case of the items grouped under efficiency, made the data concerning some of the items appearing under control and cleanliness, of little value in their relation to house-heating conditions. The lack of a satisfactory method of making tests, or of one generally accepted as such, was apparent. Under these circumstances it was deemed advisable to make a series of tests according to the A. S. M. E. code for conducting boiler trials. Accordingly, the tests herein reported have been, in the main, run in accordance with the recommendations contained in that code. The purpose of the tests thus becomes twofold; first, to obtain the information usually obtained from boiler trials when operating upon house-heating boilers, with various types of fuels; second, to obtain information that might assist in developing satisfactory methods for conducting house-heating boiler trials. The second end, it was thought, could best be attained by at first making use of the A. S. M. E. code. The adoption of this code as a guide in conducting the tests tends to lay the greatest stress upon questions relating to evaporation and efficiency. While not overlooking the importance of questions relating to capacity, regulation, attendance, and cleanliness, conditions were so arranged as to make evaporative performance the main item sought, and the best basis of comparison for this particular series of tests. It is, however, intended to conduct several additional series of tests in which more attention may be given to some of the other items just mentioned.

(7). *Variable conditions.*—Fuel or steaming tests in connection with boilers as small as the average house-heating boiler, and especially when carried on under the average conditions under which such boilers are operated, present difficulties which are much more pronounced than when conducting similar trials upon larger apparatus. The low rate of combustion under ordinary circumstances, and the low capacity at which the average house-heating boiler is operated, either all or part of the time, tend to make the results of different tests unsatisfactory for purposes of comparison, as it is exceedingly difficult under these circumstances to obtain uniformity of conditions between different tests. Apparently slight variations in fire conditions might have considerable influence upon results.

(*8*). *Amount of fuel consumed.*—The determination, with sufficient exactness, of the amount of fuel consumed presents difficulties in the case of small apparatus which are not encountered to the same extent with larger apparatus. The quantities of coal burned and water evaporated for tests of equal length may easily be ten or twenty times as large when testing with a power boiler as when testing with a house-heating boiler, and errors in determining these quantities may readily be a much greater percentage of the total in the case of the small boilers. Errors of this kind are in general most likely to occur at the beginning or end of the test, as in judging the amount of fuel consumed, or determining the weight of the water in the boiler. Probably the most noticeable error of this kind is to be found in the usual or so-called alternate method of starting and stopping boiler trials. The alternate method of the code of the American Society of Mechanical Engineers for conducting boiler trials provides for beginning and ending the test when the fire conditions are such that equal amounts of unconsumed combustible and of ash are upon the grate for the two times under consideration. That this condition may be met requires judgment and careful operation. In the average power boiler trial the fuel burned and ash removed amount to many times that which may be upon the grate at the start or stop of the test, and a mistake in judging the fire conditions at those times will make a comparatively small error in subsequent calculations. This, however, is recognized as a possible source of error of considerable importance, under the most favorable conditions, when testing power boilers. In the case of very small boilers, especially in those having a comparatively deep fire bed such as is often used in house-heating boilers, the quantity of fuel upon the grate at the beginning and end of a test would be a very considerable proportion of the total fuel burned, unless the test was of considerable length. About the same assumptions with regard to the two types of boilers would show that the error expressed in per cent of fuel consumed might readily be four or five times as great in the case of the house-heating boilers as in the case of the power boilers.

(*9*). *Standard method for starting and stopping test.*—This difficulty can be met in two ways. The test can be made longer, in which case the error becomes correspondingly smaller as expressed in per cent, or a method of starting and stopping the test can be employed, intended to eliminate or diminish the error. The standard method of the code of the American Society of Mechanical Engineers provides for the raising of steam pressure by means of a preliminary fire, withdrawing that fire and beginning the test with a new fire built with a known weight of fresh wood and coal. At the end of the test, the fire remaining is drawn and allowed for in subsequent calculations. When testing power boilers the standard method occasions some additional work and trouble, and there is considerable difference of opinion even among experts as to which method, the alternate or the standard, is the better. By far the greater number of boiler trials are probably begun by the alternate method, on account of that being the more convenient, and because of this lack of definiteness as to which method is the better. In the case of the house-heating boiler the comparatively large amount of fuel upon the grate; the lack of uniformity of fire conditions at different times during the test; the difficulty of duplicating fire conditions as desired; and the difficulty of accurately estimating the amount of unconsumed fuel and ash in the fire-box, make the alternate method of starting and stopping unsatisfactory, and necessitate some plan more in accordance with the standard method, in order that the fuel consumed may be determined with sufficient accuracy.

(*10*). *Tests by societies and individuals.*—Societies and individuals interested in this kind of work have from time to time reported tests, or discussed methods for making such tests, but apparently without making definite recommendations that have been found satisfactory for the guidance of others, or that have been adopted generally enough to make comparisons possible or of value. The number of tests of this kind which have been reported is surprisingly small as compared with the number of tests conducted upon power boilers. Probably the greatest amount of work in this line has been done by the manufacturers of heating apparatus. The results of their investigations are, however, either not available or are applicable to particular makes of apparatus only, rather than to the problem as a whole.

4. *Fuel*

Table 1 presents in tabulated form the different kinds or types of fuels tested, the section of the country from which they were received, and their size.

TABLE 1

Description of Fuels Tested

Kind or Type of Fuel	Commercial Name	Size inches	Source of Fuel
Anthracite	Egg	2¾ to 2	Wyoming District, Pa.
Pocahontas	Lump	*	Mercer County, W. Va.
Coke—Gas-house by-product	Crushed	3½ to ¾	Mnfd. by U. & C. Gas Co., from Youghiogheny coal
Coke—Solvay process	Crushed, Nut size.	1¾ to ¾	Obtained from Chicago market
Illinois	Nut	1¾ to 1	Williamson County
Illinois	Screened lump	*	Macon County
Illinois	Screened lump	*	Vermilion County

* All large lumps were broken to pieces 6 inches or less in diameter.

The fuels here listed are fairly representative of those used in house-heating work in the state of Illinois, namely: anthracite coal, eastern bituminous coal, coke and Illinois coal. The Illinois coals are typical of those most commonly used in this section of the State, coming from the southern, eastern, and central portions of the State. These fuels were purchased in the local market, either Champaign or Urbana, in lots of three tons or less, with the exception of the Solvay coke, which was obtained from the Chicago market. The anthracite and the Illinois coal from Macon County were, judging from the appearance, rather below the average quality of coal of these kinds as they appear in this market. Chemical analyses, given in Table 12, page 74, Appendix A, give more exact information as to the exact composition of all of the fuels used. Taken as a whole, however, judging from general appearances, these fuels were fair samples of what the average householder might expect to obtain.

5. *Methods of Conducting Tests*

(*1*). *Starting and stopping the test and handling the fire.*—The methods recommended by the A. S. M. E. code for conducting boiler trials were in general followed in conducting these tests. The tests varied in length from 7.97 hours to 26.53 hours. With each fuel, tests approximately 8, 16, and 24 hours long were made upon each of the two boilers. The standard method of starting and stopping the trials as prescribed by the A. S. M. E. code was used. Steam pressure was raised by means of a preliminary fire, and the boiler run at a pressure of at least five pounds for a short time to insure fairly uniform conditions in and around the boiler. The preliminary heating usually required about one hour. At the start of the tests the preliminary fire was rapidly removed and a fresh fire started with a weighed amount of wood and the first charge of coal. The test was started when the wood was ignited, at which time observations of time, water-levels, and pressures were taken. The kindling and entire amount of first charge of coal were ordinarily fired before the fire was lighted. The only exceptions to this were in cases where the kindling was ignited by the hot grates before all of the coal was fired. This, however, only delayed the firing of the entire charge of coal a few minutes after the start of the test. In all tests made with Boiler D_1, 75 lb. of fuel were fired at a time, and in all tests made with Boiler D_2, 105 lb. of fuel were fired at a time. These amounts, as compared with each other, are closely proportional to the grate surfaces of the two boilers. On account of all fuel charges being the same in amount, and also on account of the fact that a test was not ended until the fuel was so completely burned that pressure could no longer be maintained, many of the tests varied considerably from the 8, 16, or 24-hour period under which they are classed. A pressure of approximately five pounds was carried on the boiler. After a charge of fuel had been fired, the fire was not again touched until the next firing, if the automatic regulation was sufficient to keep up steam pressure without other attention. In case it became necessary in order to maintain pressure, there being plenty of unconsumed fuel in the furnace, the fire was poked or otherwise worked as seemed desirable.

(2). *Method of firing.*—For the tests with anthracite, coke and Pocahontas coal the fuel was fired by the spreading method, that is, the fresh fuel was spread about evenly over the entire grate surface. For the Illinois coals, on account of the liability of explosions due to gas collecting in the combustion chamber and flues, it was deemed advisable to fire by a method approaching the coking method. With the boiler D_1 the fresh fuel was fired more heavily at one side of the furnace than at the other, allowing the fire to burn up brightly much more quickly upon the side thinly fired than would otherwise have been the case. With boiler D_2 the burning fuel which remained in the furnace just before firing, was in part pushed or raked toward the rear of the grate, and the greater part of the fresh charge fired in front. This allowed the fire upon the back part of the grate to burn brightly almost from the time of firing.

(3). *Attention.*—The effort was made throughout to reduce to a minimum the amount of attention given the fire between times of firing. The attention which the fire did receive, however, which might be considered as additional to what would be expected in ordinary house-heating work, was given in accordance with the desire to have the tests fairly comparable upon an evaporative performance basis, rather than to obtain data relative to attendance conditions.

(4). *Ash and residual fuel.*—The fire was drawn at the end of the test, when the boiler pressure dropped below four or five pounds on the last firing, and did not again rise upon the opening of the damper and the closing of the check. Just as the grate was dumped, final observations concerning time, water, temperatures and pressures were taken. The material drawn out at the close of the test was immediately put into a galvanized can with a close fitting cover to prevent further combustion. Analysis of this partly consumed or residual fuel furnished suitable corrections in the determination of the amount of fuel actually burned. The ash was kept separate from the residual fuel, being taken from the furnace and ash-pit before the fire was drawn.

(5). *Sampling of fuel, ash and residual fuel.*—The fuel was sampled in the usual manner by taking a small portion from each firing. The sample so collected varied from about 5 per cent to 10 per cent of the total fuel fired. It was collected in a can with a closely fitting cover, and, within a few hours after the close of the test, was thoroughly mixed, crushed to ¼ in. size or smaller, and quartered until a 1000 gram sample was obtained. This 1000 gram sample, placed in a suitable pan, was air-dried and then transferred to the Chemical Laboratory in glass jars for the purpose of chemical analysis.

The ash and residual fuel were each run through a laboratory crusher reducing them to pieces ¼ in. or smaller. They were then quartered, accompanied with thorough mixing, until samples were obtained of each, which would about fill a one quart glass jar.

(6). *Chemical analyses.*—All chemical analyses were made at the chemical laboratories of the University of Illinois. Proximate analyses and calorific determinations of the fuel were made for each test or for each group of two tests, where the two boilers were operated simultaneously upon the same fuel. The ash and residual for each test were analyzed for carbon and earthy matter. Ultimate analyses were made from composite samples for each fuel tested. The composite samples were made by combining from each of the air-dried samples an amount proportional to the fuel burned as represented by each sample. Calorific determinations were made in a Mahler-Atwater oxygen calorimeter. In Table 12, page 70, will be found analyses of the ash and residual fuel as to carbon and earthy matter, and the proximate analyses of the fuel for each test.

In Table 2 are given the proximate and ultimate analyses of the fuels as made from the composite samples.

TABLE 2

Analyses of Composite Samples

Per Cent

Kind of Fuel	Proximate Analysis Fuel as Fired				Ultimate Analysis Dry Fuel					
	Fixed Carbon	Volatile	Moisture	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash
Anthracite	77.68	7.07	3.47	11.78	81.33	2.12	1.82	0.91	1.61	12.21
Pocahontas	73.43	19.50	1.90	5.17	84.20	4.79	3.61	1.14	1.00	5.26
Gas House coke	81.74	2.74	5.73	9.79	86.05	0.83	0.41	0.91	1.41	10.39
Solvay coke	85.76	2.45	1.51	10.28	86.84	0.58	0.28	1.21	0.65	10 44
Illinois, Williamson county	48.42	36.28	6.66	8.64	71 62	5.19	10 29	1 53	2.11	9.26
Illinois, Macon county	40.56	37.67	10.01	11.76	66.98	4.63	10.34	1.42	3.56	13.07
Illinois, Vermilion county	40.35	39.57	11.14	8.94	73.22	4.43	8.29	1.52	2.48	10.06

TABLE 3

Average Proximate Analyses of Fuel as Fired

Per Cent

Kind of Fuel	Fixed Carbon	Volatile Matter	Combustible (Carbon + Volatile)	Moisture	Ash	Sulphur	Calorific Value B. t. u. per lb.
Anthracite	78.55	5.77	84.32	3.93	11.75	1.17	12682
Pocahontas	73.33	19.49	92.82	2.01	5.17	0.98	14753
Gas House coke	80.68	3.34	84.02	5.92	10.06	1.15	12053
Solvay coke	85.80	2.14	87.94	1.60	10 46	0.65	12505
Illinois, Williamson county	48.07	36.27	84.34	6.55	7.27	2.09	12275
Illinois, Macon county	40.84	37 56	78.40	10.24	11.36	3.19	11065
Illinois, Vermilion county	40.36	39.53	79.89	11.18	8.93	2.21	11546

Table 3 gives values for the proximate analyses of the different fuels obtained by averaging the values for all tests with each fuel. The averages included in this table are computed by giving weights to the values for each test proportional to the weight of fuel fired. A comparison of the average values for each fuel, as contained in this table, with the corresponding values of the proximate analyses made upon the composite samples exhibits some differences which are, however, for the most part, small. The average calorific value, determined for each fuel in the same manner as the other averages has been included in Table 3.

(*7*). *Feed water.*—The feed water delivered to each boiler through the measuring tanks was condensation from heating coils, and the effort was made to feed the water at as nearly constant a rate as possible, and at a temperature which might correspond fairly well with that of the returns in house-heating work. The feed water temperature averaged about 175° F.

(*8*). *Loading.*—For all tests a load equivalent to about 65 per cent of the boiler rating was maintained by means of a suitably sized orifice in the outlet. The evaporation of 0.3 lb. of water from and at 212° F. was assumed as equivalent to serving one sq. ft. of radiation for one hour. A pressure of 5 lb. controlled by the automatic regulators, which are a part of the boilers, was maintained at the boiler. The pressure after leaving the boiler was reduced to slightly over 2 lb. in the receiver, so that a difference of 2 lb. pressure was maintained between the two sides of the orifice. Recording gages were used in order that the variations in boiler pressure might be readily observed during the course of the test.

(*9*). *Temperatures.*—A recording pyrometer was used in connection with most of the tests made upon Boiler D_1, for the purpose of taking flue gas temperature. For the remainder of the tests upon boiler D_1, and for all tests upon D_2, mercury flue gas thermometers reading to 1000° F. were employed. A recording thermometer for outdoor temperatures was also employed.

(*10*). *Smoke and flue gas analyses.*—Smoke records were taken for each test, generally for a period extending from the time of one firing to the time of the next firing. The flue gas samples were, as a rule, taken as continuous samples, each over an interval of time of one hour. At times continuous samples were taken extending over the entire time between two firings. These samples were analyzed in an Orsat apparatus of the common type.

(*11*). *Cleaning flues.*—The boiler flues were cleaned previous to each test in order that conditions in this respect might be approximately equal. On account of the preliminary fire, there was doubtless always some soot on the flues at the start of the test proper, as it was not considered advisable to open up the boiler for cleaning just before starting the new fire. Also the flues, doubtless, became coated with soot more rapidly with some fuels than with others. There would also, as a general rule, be a greater accumulation of soot and ashes in the flues for a sixteen or twenty-four hour test than for an eight hour test.

(*12*). *Miscellaneous observations.*—The following observations were taken every twenty minutes: height of water in the boiler, height of water in the feed tank, height of water in gage glass of separator, temperature of feed water, boiler room temperature, steam pressure in boiler, difference of pressure on the two sides of the orifice plate, and drafts in ash-pit, over the fire and in the flue.

6. *Test Data*

The test data were, in general, recorded in accordance with the requirements of the A. S. M. E. code and were entered upon blank forms suitably arranged for the class of work in hand.

On pages 84, 85, 86, and 87, of Appendix A will be found, Fig. 18-21, graphical logs of four tests which have been selected as representative. They are, respectively, records of tests made with anthracite, Pocahontas coal, coke and Illinois coal.

7. *Tabulated Data and Results*

In Appendix A, Table 12, will be found the principal data and results of the 48 tests under consideration; explanatory matter concerning the results accompanies the table. This material will be found upon pages 66 to 83, inclusive, of Appendix A.

In Tables 13 and 14, pages 88 and 89 of Appendix A, will be found data relative to flue gas analyses. It will be noted that the per cent of CO_2 is in general quite high. In all flue gas analyses the per cent of CO was also determined in the manner usual with the Orsat apparatus. Owing to the uncertainty as to the value of such determination these data are not here presented. In general no trace of CO was found or only a fraction of 1 per cent.

In one case, however, where the sample was taken immediately after firing, 4.3 per cent CO was found.

8. *Method of Calculating Results* The results tabulated in Table 12, Appendix A, are in general calculated by methods which are the same as those employed in calculating boiler trials made under the A. S. M. E. code.

Throughout all calculations involving capacity the evaporation of 0.3 pounds of water from and at 212° F. has been used as equivalent to serving one square foot of radiation for one hour.

In the calculation of item 23.2 tabulated on page 72, which is the total dry fuel fired minus the dry fuel equivalent of the ash and of the residual fuel, it was assumed that the ash and the residual fuel consisted of earthy matter and carbon only. The carbon found in the ash and the residual fuel by analysis was assumed to have a heating value of 14600 B. t. u. per lb. and was converted to dry fuel by dividing the total number of B. t. u. so found by the B. t. u. value of one pound of dry fuel under consideration.

9. *Discussion of Results*

A. Efficiency and Evaporative Performance

(1). Efficiency and fixed carbon content.—An examination of item 62 as given in Table 12, page 82, shows that the plant efficiencies varied from 44.76 per cent to 66.21 per cent. In Fig. 1 these efficiencies have been plotted for each test to a base, expressed in per cent, of the fixed carbon content of the coal. These points fall into two groups due to the low fixed carbon content of the Illinois coals as compared with the other fuels. The tendency of low efficiency to go with low fixed carbon content is, however, marked, and emphasizes the fact that in this respect the fuels high in fixed carbon content are much better adapted to present methods of house-heating. The Illinois coals may be considered as the natural fuel supply for this state and section and the problem becomes one of adapting methods and equipment to the burning of these coals at efficiencies at least approximating those of fuels like anthracite and coke.

(2). Efficiency with Pocahontas coal.—The lowest plant efficiences recorded are for tests made with Pocahontas coal. The average plant efficiency with Boiler D_1 for this fuel was 44.97 per cent and with Boiler D_2 55.43 per cent. A partial explanation of

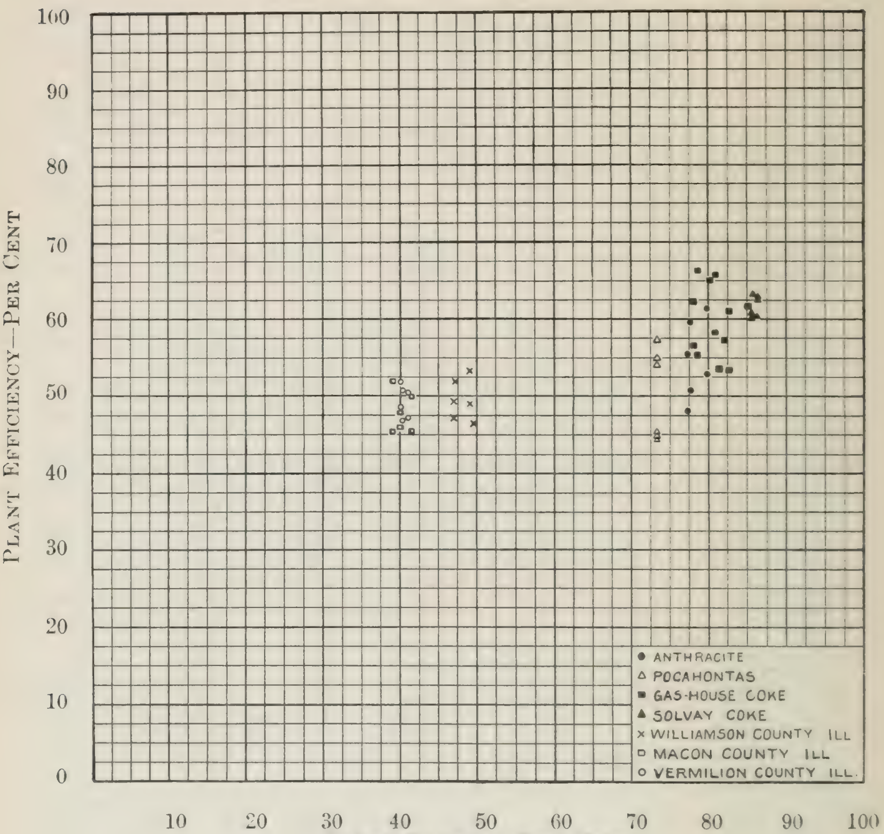

Fig. 1 Relation of Efficiency to Fixed Carbon

these low plant efficiencies for the Pocahontas coal is to be found in the fact that a comparatively large amount of unconsumed fuel passed through the grate with the ash. The per cent of carbon in the ash for Pocahontas tests varied from 50 to 70 per cent, being much higher than with any other fuel tested. The Pocahontas coal used contained a large amount of very fine coal which is the usual condition of this fuel in this market.

The efficiency of the boiler and furnace alone, excluding the effect of coal dropping through the grate, is, however, also low in the case of the Pocahontas coal. These efficiencies will be found under item 61, Table 12, page 82 and average values of the same in Table 6, page 36. The use of Pocahontas coal for house-heating purposes is quite common in this section and when used is generally highly thought of for such work, having merits that may warrant its use in spite of low evaporative efficiency. Of the several fuels tested it has the highest heat content as expressed in B. t. u. contained. The small number of tests here reported precludes the possibility of drawing definite conclusions in regard to the efficiency that may be obtained with this fuel under the various conditions under which it may be consumed, while the wide variation in the efficiencies obtained, especially as between the two boilers, indicates the possibility of adapting fire conditions and equipment to the requirements of the fuel in order to obtain higher efficiencies.

(3). *Efficiencies of the two types of boilers.*—There has been no attempt in this article to compare or discuss the merits of the boilers used in making the tests, the tests having been conducted with the idea of comparing the fuels rather than the apparatus. In the case of Pocahontas coal, as mentioned above, it was found that one boiler was operating much more efficiently (measured by evaporation) than the other. When testing the two kinds of coke it was found that in the case of the Solvay coke the efficiencies for the two boilers were not greatly different, while when testing with the gas-house coke they differed greatly. It will be noted that in the tests reported there are six tests with each fuel except in the case of the gas-house coke, with which fuel twelve tests were made. The series of tests upon the gas-house coke was duplicated as a check in regard to this difference in performance. The coke was chosen as being a fuel with which constant fire conditions could be readily maintained and with which any discrepancy would be most easily detected, although the difference in efficiency as between the two boilers was the most marked in the case of Pocahontas coal. The second set of tests with the gas-house coke did not show material differences in regard to efficiencies from those shown by the earlier tests. The principal difference between the two cokes, aside from a slightly higher volatile content in the gas-house coke was the smaller and much more uniform size to which the Solvay coke was crushed. Fire conditions were much more uniform when burning the Solvay coke and it seems probable that efficiencies were much more affected by varying chemical or physical characteristics of the fuel in the case of the boiler with the comparatively small amount of heating surface.

(4). *Variations in efficiency.*—Efficiencies as determined by fuel tests with house-heating boilers apparently vary greatly with varying conditions of fuel and fire and should be compared only with the greatest care. Omitting considerations which relate to the boiler and furnace employed, the composition of the fuel is probably the most important factor to be considered. A coal high in fixed carbon so that combustion may be completed on or near the grate will give high efficiencies, a coal high in volatile matter which, when burning, gives off large volumes of rich gases that may or may not be burned, will give low efficiencies. The high volatile fuels are, as a rule, of approximately the same calorific capacity as the high carbon fuels, while if based upon the cost per B. t. u. they are much cheaper. The problem in this particular respect (not considering cleanliness, control, etc.) then becomes one of determining the conditions which will permit of burning the high volatile coals at efficiencies at least approximately equal to those of the high carbon coals, or stated somewhat differently, the conditions which will permit of burning Illinois coal, the cheap and natural supply, instead of the fuels which must be transported long distances and sold at correspondingly high prices. For the tests here considered it is believed that decided differences in efficiency were caused by various fire conditions due to the size of fuel burned and to the per cent of fine material contained therein, to the degree with which the fire bed coked, burned evenly over the grate or burned holes through and around itself, also to the extent to which the gases first distilled from a fresh charge of fuel were burned or passed away unconsumed. While efforts were made throughout the tests to keep fire conditions uniform, it not being the purpose of the tests to study efficiency under varying conditions, such variations as did occur point to the possibility of improving efficiency by proper attention to details relating to fuel, operation and equipment.

(5). *Efficiencies as compared with those of power boilers.*—Under conditions comparable to the tests made efficiencies ranging from 40 per cent to 70 per cent may be expected. These efficiencies are somewhat, though not greatly, lower than corresponding figures upon power boilers.

(6). *Illinois coal.*—The efficiencies obtained indicate the desirability of improvement in order that Illinois coal may be placed more nearly on an equal footing with other fuels in this respect when employed for house-heating purposes.

(7). *Evaporative performance.*—The equivalent water evaporated from and at 212° F. per sq. ft. of heating surface varied in the case of boiler D_1 from 3.36 lb. to 3.91 lb. and in the case of boiler D_2 from 2.48 lb. to 2.89 lb. If these small boilers were rated upon 10 sq. ft. of heating surface to 1 b. h. p., which is equivalent to an evaporation of 3.45 lb. per sq. ft., when operating at 100 per cent capacity, then boiler D_1 under the test conditions was evaporating water at quite as high a rate as is usual in power boiler work, while boiler D_2, owing to its greater heating surface, was evaporating water at a somewhat lower rate, but still at one which is by no means uncommon in ordinary power boiler work. When it is remembered that these boilers were operating at approximately 65 per cent of their rated capacity it will be seen that high rates of evaporation would be required if they were operated at 100 per cent rated capacity, or if forced to an overload. The variable demand upon the house-heating boiler will at times necessitate very high or very low rates of evaporation per square foot of heating surface, and the nature of the service may readily warrant somewhat inefficient performance under these conditions in order that the equipment be comparatively small, simple in construction and easily operated. It would appear, however, that a rate of evaporation much higher than has been found economical or advisable in power boiler work should also be avoided in house-heating boiler work if that be possible, and the effort should be made to so adapt the fuel and equipment that a rate of evaporation would be obtained which under average operating conditions would be most apt to be accompanied by high efficiency.

(8). *Average operating conditions.*—The conditions under which house-heating boilers operate are so varied that it is impossible to state any given per cent of their rated capacity as even approximately that of average operating conditions. A boiler used for heating an office building, school house, or in work of a similar character might be operated at a relatively high average capacity as high or higher than 65 per cent as obtained in the tests under consideration, while in residence work on a small scale a boiler may only be required to operate at a high capacity for a few hours each day and the average load may not be more than 20 per cent of the rated capacity.

(9). *Efficiency and capacity.*—The arrangement and amount of heating surface advisable for low capacities may be unsuited for high capacities and deductions in regard to any particular feature of house-heating boiler performance must be made with regard for such conditions. The tests here considered have all been run at practically one capacity (65 per cent of the rated capacity) and give little information in regard to efficiency as affected by varying capacity. The uniformly lower efficiency of boiler D_1 as compared with boiler D_2 with the corresponding high evaporation per square foot of heating surface would indicate that high rates of evaporation per square foot of heating surface due to reduced heating surface tend toward low efficiency at least in the neighborhood of the capacities at which the tests were run. A series of tests is now under way operating these boilers at capacities varying from about 10 per cent to 100 per cent of their rated capacity in order to throw further light upon the relation of efficiency to capacity. The rated capacities of D_1 and D_2, 800 and 1075 square feet of radiation, respectively, are closely proportional to the fuel capacity of the fire-boxes, while the ratio of capacity (expressed in square feet of radiation) to the total heating surface is much higher in the case of boiler D_1 than of D_2, that is, when operating at full capacity one square foot of heating surface in boiler D_1 must serve 18.2 square feet of radiating surface while for boiler D_2 one square foot of heating surface serves only 14.2 square feet of radiation. The ratio of direct to total heating surface is higher in the case of D_1 than of D_2.

B. Length of Tests and Method of Conducting

In order to determine what length of test was best in order to secure data of a satisfactory character, tests of eight, sixteen, and twenty-four hours were run with each fuel upon each boiler. The principal item affected by the length of the test is the amount of fuel consumed, which in turn affects many of the other important calculated items. The difficulties attending the determination of the amount of fuel consumed have been discussed and the manner in which the longer test tends to eliminate the errors which occur.

(*1*). *Fuel consumption.*—Fig. 2-5, pp. 27-30, show the coal as fired, plotted on a time base, for each test made with four of the fuels tested. In all cases the slope of the coal line representing the period of the first charge of fuel is steeper than the slope of the line of subsequent firings. This is particularly marked in the case of the anthracite. An examination of the line

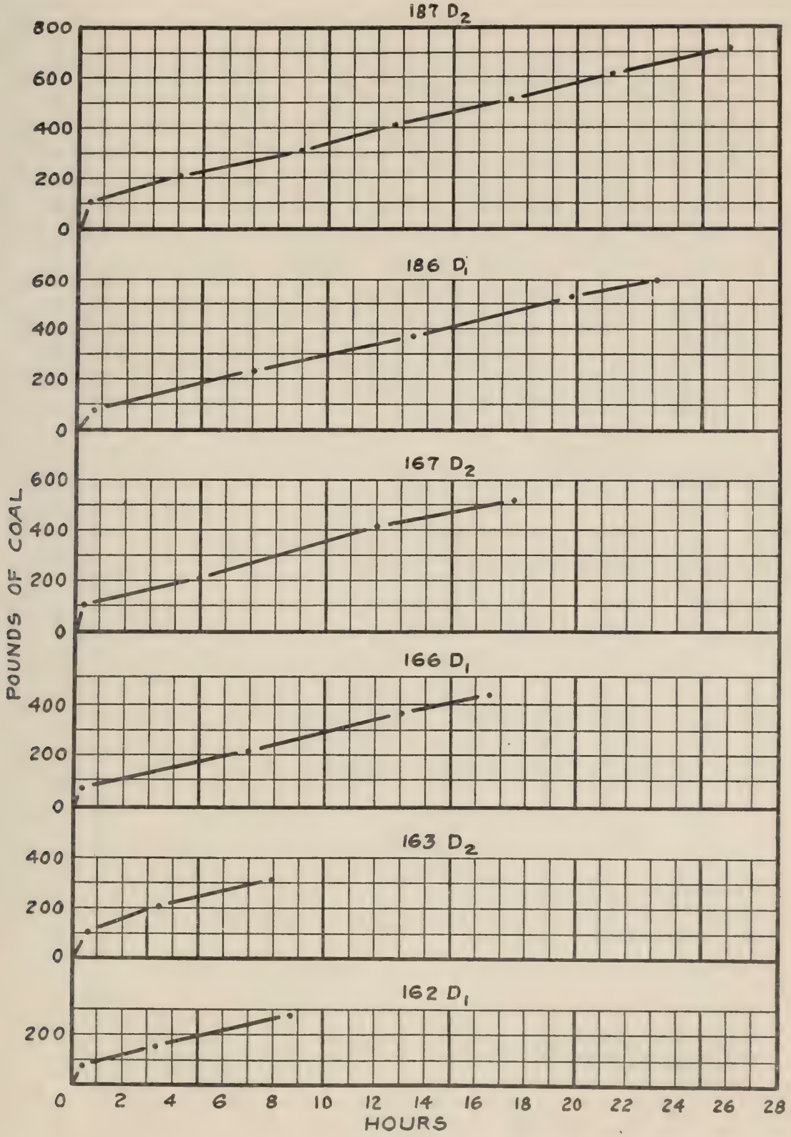

FIG. 2 FUEL CONSUMPTION—ANTHRACITE COAL

representing the second firing will in some cases disclose the fact that some unconsumed fuel remained in the fire-box at the time of the second firing and was then burned, making that period somewhat longer than subsequent periods. The time of the last

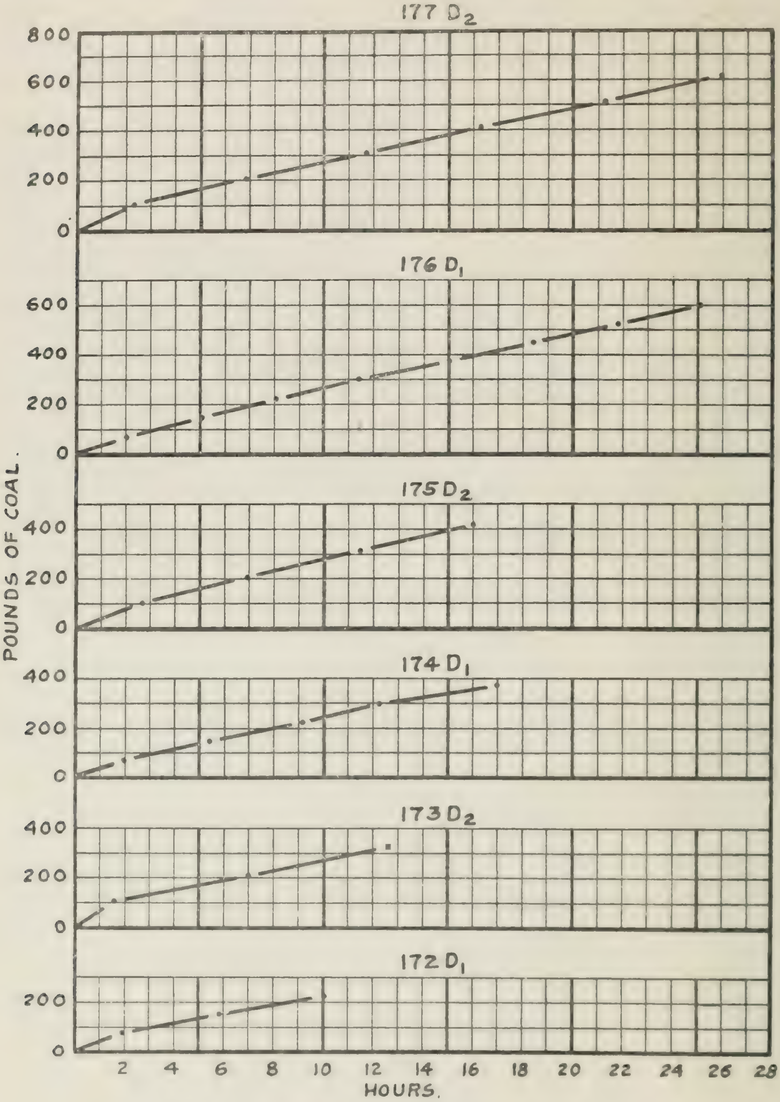

FIG. 3 FUEL CONSUMPTION—POCAHONTAS COAL

firing will also be noted as often being longer than the preceding periods on account of the fire being allowed to burn out somewhat more completely at the end of the test than was usual at the end of the other firing periods. As a rule, however, after the first firing the slope of the coal line is quite uniform, and it was the general opinion of the observers that after the first or second

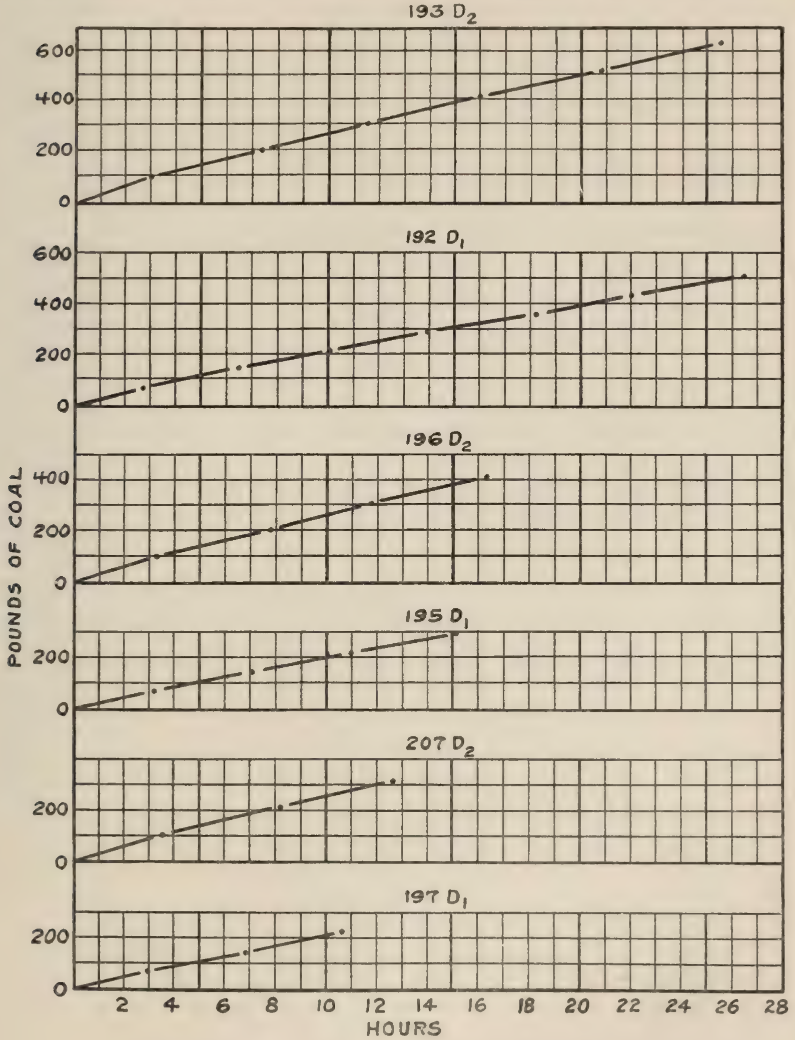

FIG. 4 FUEL CONSUMPTION—SOLVAY COKE

firing period the test conditions could readily be kept practically uniform for any reasonable length of time. At the beginning of this series of tests it was thought possible that after making the

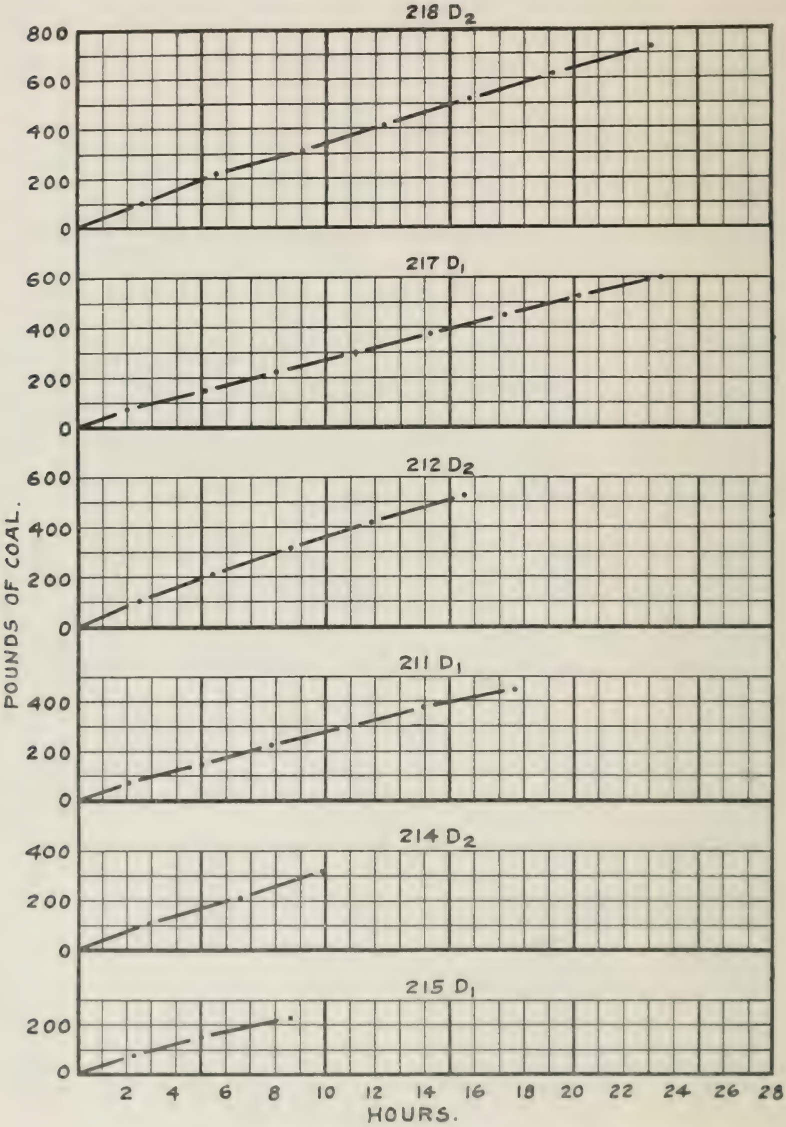

FIG. 5 COAL CONSUMPTION—ILLINOIS COAL (WILLIAMSON CO.)

tests, starting and stopping by the method adopted, it might be possible to divide the data so as to omit one or more of the firing periods, such as the first, or first and last periods, retaining only those periods as a portion of the test during which conditions were apparently constant. This would in effect give a test using the alternate method of starting and stopping. It has, however, not been thought advisable to attempt such a division of the data and discussion of it here. Many of the tests consisted of but three or four firing periods and the elimination of one or more periods would make the duration of the test extremely brief and correspondingly magnify errors due to the varying fire conditions. The methods adopted for determining the amount of fuel consumed were found to be very satisfactory and it seemed that little or nothing was to be gained by discussing the data upon a basis which might give less accurate values for that important item.

(*2*). *Efficiency and evaporation as affected by length of test.*—Table 4 shows the equivalent evaporation and efficiencies for all tests, grouped as tests 8, 16 and 24 hours long. The same data are plotted in Fig. 6 and 7. In the majority of the tests the rates of evaporation and efficiencies are higher for the 16-hour tests than for the 8-hour tests. This condition is true to a more marked extent in the case of boiler D_1 than of boiler D_2. The lower efficiencies, in general, of the 8-hour tests may be due to losses incurred through inefficient burning during the first fire which would affect the results of the shorter tests to the greater extent. Accumulations of soot in the flues of boiler D_2 and the extent to which this soot was burned out during the tests may have affected efficiencies to a considerable extent. Comparing the rates of evaporation and efficiency for the 16-hour and 24-hour tests the differences are in general not so great as between the 8 and 16-hour tests.

No complete explanation is here offered as to the cause of this variation in the matter of efficiency and rate of evaporation per pound of fuel for tests of different length. In some individual tests varying conditions which were noted were thought to have caused these changes either in part or altogether, but no general conclusion in this respect could be drawn. It was, however, considered that 16-hour tests would give results more reliable and better for comparative purposes than 8-hour tests and that as be-

TABLE 4

EQUIVALENT EVAPORATION AND EFFICIENCY FOR DIFFERENT LENGTHS OF TESTS

	8-hour Test			16-hour Test			24-hour Test		
	Length of Test	Equivalent Evaporation Per Pound of Fuel as Fired	Efficiency of Plant	Length of Test	Equivalent Evaporation Per Pound of Fuel as Fired	Efficiency of Plant	Length of Test	Equivalent Evaporation Per Pound of Fuel as Fired	Efficiency of Plant
	hours	pounds	per cent	hours	pounds	per cent	hours	pounds	per cent
BOILER D1									
Anthracite	8.77	6.32	48.07	16.55	6.67	50.58	23.15	6.68	52.59
Pocahontas	10.07	6.84	44.76	17.03	6.90	45.18	25.13	6.87	44.98
Gas House Coke	8.43	6.65	53.43	15.83	6.74	53.33	23.70	7.08	56.46
Gas House Coke	9.57	6.69	55.23	17.15	7.15	57.26	26.23	7.19	58.16
Solvay Coke	10.63	7.75	60.47	15.17	8.02	62.58	26.53	7.85	60.32
Illinois, Williamson county	8.63	5.86	46.42	17.68	6.05	47.17	23.48	6.19	48.99
Illinois, Macon county	9.78	5.19	45.46	16.73	5.24	45.94	24.58	5.18	45.53
Illinois, Vermilion county	7.97	5.53	46.88	16.45	5.78	47.14	24.47	5.73	48.50
BOILER D2									
Anthracite	8.00	7.26	55.22	17.52	7.87	59.68	26.00	8.01	61.23
Pocahontas	12.65	8.25	53.99	16.05	8.38	54.87	25.93	8.77	57.42
Gas House Coke	11.85	8.02	66.21	15.55	7.99	61.51	24.85	8.12	65.69
Gas House Coke	11.70	7.99	65.05	14.92	7.72	61.08	24.17	7.80	62.20
Solvay Coke	12.58	8.29	63.27	16.32	8.11	63.28	25.55	7.87	60.47
Illinois, Williamson county	9.88	6.61	51.93	15.58	6.33	49.35	23.18	6.73	53.26
Illinois, Macon county	8.38	5.93	51.95	16.03	5.48	48.04	23.13	5.71	50.18
Illinois, Vermilion county	8.55	5.97	50.61	15.07	6.18	50.40	25.02	6.12	51.80

tween tests 16 and 24 hours long the results of the shorter tests would in general be as serviceable as those of the longer ones.

(3). *Length of test required.*—Basing a conclusion as to the length of test desirable upon the work here reported for tests which are comparable to these tests as to load conditions, that is, operating at fairly high capacity, as 50 per cent or more of rated capacity, it would seem advisable to make the test at least 16 hours long and to have at least three firing charges. The stop should be made according to fire conditions, rather than at the end of a given interval of time. In case the firing charges were large or the load light, the length of the test might with advantage be somewhat longer than 16 hours. The length of 16 hours is given as approximately the minimum time which would give results that could be considered as satisfactorily comparable. Under the test conditions the 8 hour tests were liable to be considerably affected by the varying fire conditions at the start and stop of the test, while it seemed that after about 16 hours little was gained by running the test through 24-hour or longer periods. It is likely, however, that for service tests with very variable

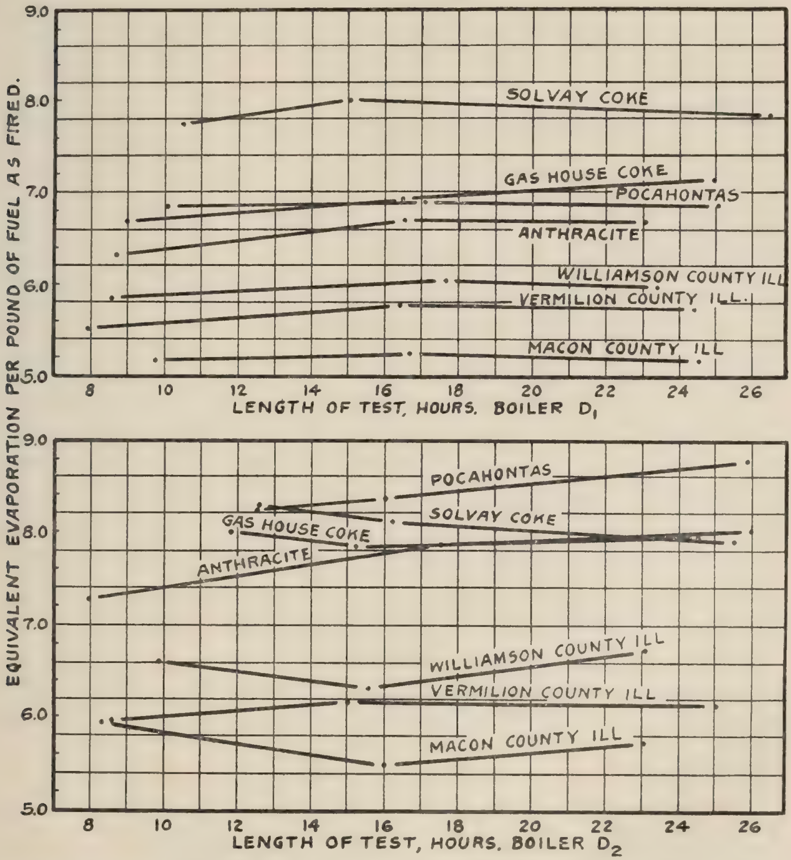

Fig. 6 Relation between Length of Test and Equivalent Evaporation per Pound of Fuel as Fired

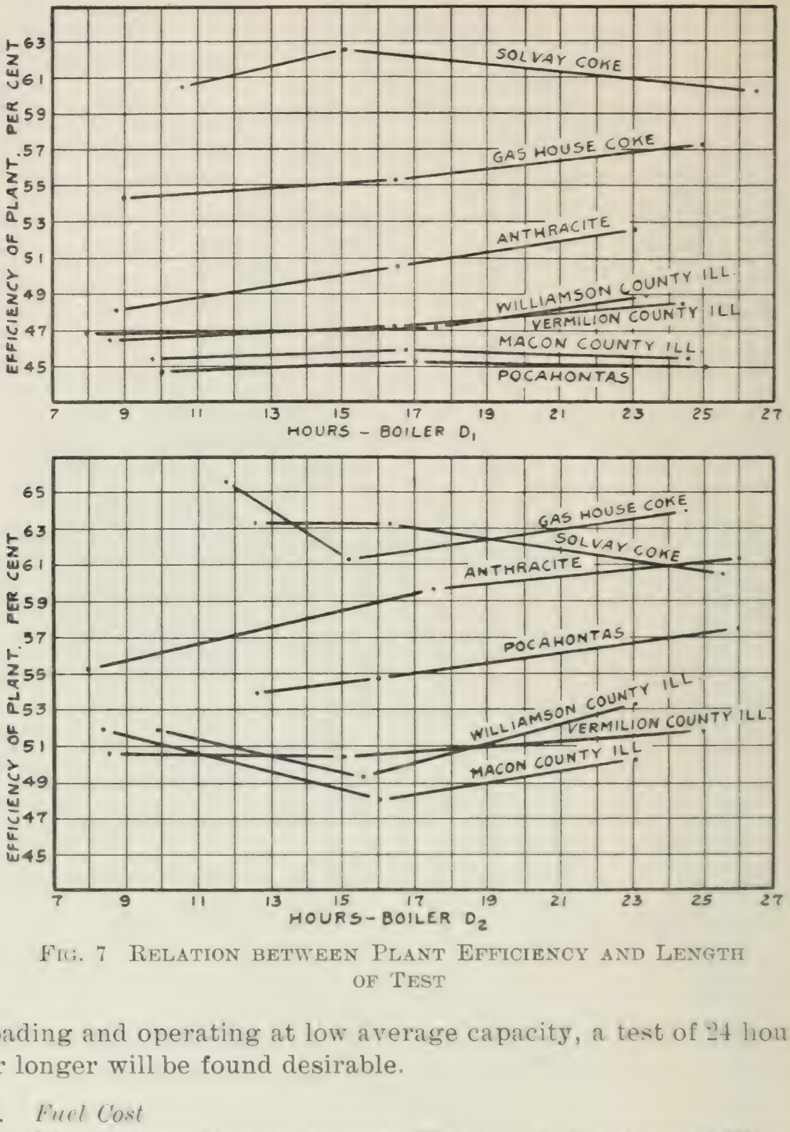

FIG. 7 RELATION BETWEEN PLANT EFFICIENCY AND LENGTH OF TEST

loading and operating at low average capacity, a test of 24 hours or longer will be found desirable.

C. Fuel Cost

(*1*). *Price and heating value.*—The great advantage of Illinois coal for the Illinois user and others within a reasonable distance of the field is in its low price. First-class Illinois coal for domestic purposes can be purchased for one-half or less than one-half the price which must be paid for anthracite. While the heating

TABLE 5

RELATIVE COST OF FUELS

Kind of Fuel	B. t. u. per Pound of Fuel as Fired	Cost of 14600 B. t. u. cents	B. t. u. per 1 cent	Cost of 14600 B. t. u. Based on Anthracite as 100% (per cent)	B. t. u. in per cent Based on Anthracite as 100%	Cost per Ton of 2,000 lbs. in Local Market	Cost in per cent Based on Anthracite as 100%
Anthracite	12682	0.47	30417	100	100	$8.25	100
Pocahontas	14753	0.27	54074	57.4	116.3	5.50	66.6
Gas House Coke	12053	0.30	48667	63.8	95.0	5.00	61.0
Solvay Coke	12505	0.35	41714	74.5	98.6	6.00	72.7
Illinois, Williamson county	12275	0 22	66364	46.8	96.8	3.75	45.5
Illinois, Macon county	11005	0.23	63478	48.9	86,8	3.50	42.4
Illinois, Vermilion county	11546	0.18	81111	38.3	91.0	2.85	34.5

value of the anthracite and other high-priced fuels is in general greater than the Illinois coals, the difference is not so great as to be in any sense commensurate with the difference in price. Table 5 gives information concerning the relative cost of the fuels tested. The heating value of the Pocahontas coal is considerably higher than the other fuels, that of the anthracite somewhat higher than the Illinois coal, while the cokes have approximately the same heating value as the highest given for the Illinois coal. It will be noted that the B. t. u. (British thermal units)per pound of anthracite is 12682 as compared with a value of 12275 for a comparatively high-priced Illinois coal and a value of 11546 for a somewhat cheaper Illinois coal. In one case the Illinois coal costs 45.5 per cent of the price of the anthracite and contains 96.8 per cent of its heating value. In the other case the Illinois coal costs but 34.5 per cent of the price of the anthracite and contains 91 per cent of its heating value. While it is recognized that under present conditions the heat content alone is by no means a sufficient measure of the value of the coal, this great discrepancy in price per heat unit suggests the need of improvement in the methods of burning the cheaper fuel. If all other advantages or disadvantages could be equalized or eliminated, the B. t. u. delivered by the fuel would be the direct measure of its value.

(2). *Relative cost as shown by tests.*—Table 6 presents comparisons relative to fuel costs. The values tabulated in Columns 6 to 13 inclusive are averages for all tests run with each fuel with each boiler. Columns 1 and 2 give the kind and cost of each fuel.

TABLE 6 COMPARISON OF FUEL COSTS

1	2	3	4	5	6	7	8	9	10	11	12	13
Kind of Fuel	Cost of Fuel per Ton of 2,000 lbs.	Calorific Value of B. t. u. per Pound Fuel as Fired	Cost per 14,600 B. t. u.	Cost per Pound of Fixed Carbon	Percent of Builders Rating Developed	Fuel as Fired per sq. ft. of Grate Surface per hour	Equivalent Evaporation from and at 212° F. per hour per sq. ft. of Heating Surface	Cost of Evaporating 1000 lbs. of Water from and at 212° F.	Percent Cost of Evaporating 1000 lbs. of Water from and at 212° F., Based on Cost of Anthracite as 100 Percent	Percent Saving of Cost of Anthracite	Cost of Fuel per 100 sq. ft. of Radiating Surface per hour	Efficiency of Plant [Boiler Furnace and Grate]
	dollars	B. t. u.	cents	cents	per cent	lb.	lb.	cents	per cent	per cent	cents	per cent
BOILER D1												
Anthracite	8.25	12682	0.47	0.53	66.00	5.6	3.63	62.37	100	0	1.87	50.41
Pocahontas	5.50	14753	0.27	0.38	63.88	5.2	3.51	40.04	64.2	35.8	1.20	44.97
Gas House Coke	5.00	12025	0.30	0.31	65.48	5.3	3.60	36.20	58.0	42.0	1.09	55.65
Solvay Coke	6.00	12474	0.35	0.35	64.46	4.7	3.54	38.10	61.1	38.9	1.14	61.12
Illinois, Williamson county	3.75	12266	0.22	0.39	64.04	6.0	3.51	31.09	49.8	50.2	0.93	47.53
Illinois, Macon county	3.50	11005	0.23	0.44	65.54	7.1	3.60	33.71	54.0	46.0	1.01	45.64
Illinois, Vermilion county	2.85	11552	0.18	0.35	65.13	6.2	3.59	25.14	40.3	59.7	0.76	47.51
BOILER D2												
Anthracite	8.25	12682	0.47	0.53	62.33	4.4	2.65	53.54	100	0	1.61	58.71
Pocahontas	5.50	14753	0.27	0.38	64.09	4.1	2.72	32.51	60.7	39.3	0.97	55.43
Gas House Coke	5.00	12076	0.30	0.31	62.48	4.2	2.66	31.50	58.8	41.2	0.95	63.62
Solvay Coke	6.00	12531	0.35	0.35	60.78	4.0	2.58	37.08	69.3	30.7	1.12	62.34
Illinois, Williamson county	3.75	12284	0.22	0.39	64.81	5.3	2.75	28.61	53.4	46.6	0.86	51.51
Illinois, Macon county	3.50	11005	0.23	0.44	65.74	6.2	2.79	30.70	57.3	42.7	0.92	50.06
Illinois, Vermilion county	2.85	11513	0.18	0.35	65.30	5.8	2.77	23.40	43.7	56.3	0.70	50.94

These were purchased mostly from local dealers and have already been described in the paragraph on fuels on page 14. Almost all of these fuels can be purchased somewhat more cheaply in larger quantities. Column 3 gives the heating capacity per pound for each fuel as taken from Table 3, page 18 and Column 4 the cost of 14600 B. t. u. as purchased in each. (The number 14600 B. t. u. as the calorific value of a pound of pure carbon is taken as a convenient unit for comparison.) In Column 5 is given the cost per pound of fixed carbon for the different fuels. Columns 6, 7 and 8 give three of the principal operating conditions inserted here for convenience in making comparisons and in showing the degree of uniformity of these conditions. Columns 9, 10 and 11 give the fuel cost of evaporating 1000 lb. of water from and at 212° F. and percentage relations concerning the same. Column 12 also presents the results relative to fuel cost and evaporation stated in terms of serving 100 sq. ft. of radiation. Column 13 gives averages of plant efficiencies.

(*3*). *Cost per B. t. u. and per pound of fixed carbon.*—It will be noted that the cost per B. t. u. is almost three times as much in the case of anthracite as in the cheapest of the Illinois coals. When comparing the costs per pound of fixed carbon, which under present conditions of burning is a very important consideration, the differences in price are not as marked, the cokes having the lowest cost per pound in this respect. It is to be supposed that the heat content of the fixed carbon is utilized to about the same extent for all the fuels, the variations in efficiency being largely due to incomplete utilization of the heat-content of the volatile matter. The relation of efficiency to fixed carbon content has already been shown graphically in Fig. 1, page 22. In Fig. 8 and 9 average efficiencies have been plotted with relation to cost per B. t. u. per cent volatile and per cent of fixed carbon. These figures show graphically the higher efficiencies obtained with the higher priced fuels, and those high in fixed carbon content, as contrasted with those high in volatile matter, and indicate the desirability of developing methods for burning the cheap and high volatile fuels in a more efficient manner.

(*4*). *Cost of evaporation* —The rate of combustion and rate of evaporation per square foot of heating surface are both lower in the case of boiler D_2 owing (aside from efficiency differences) to the greater grate and heating surfaces of that boiler relative to the

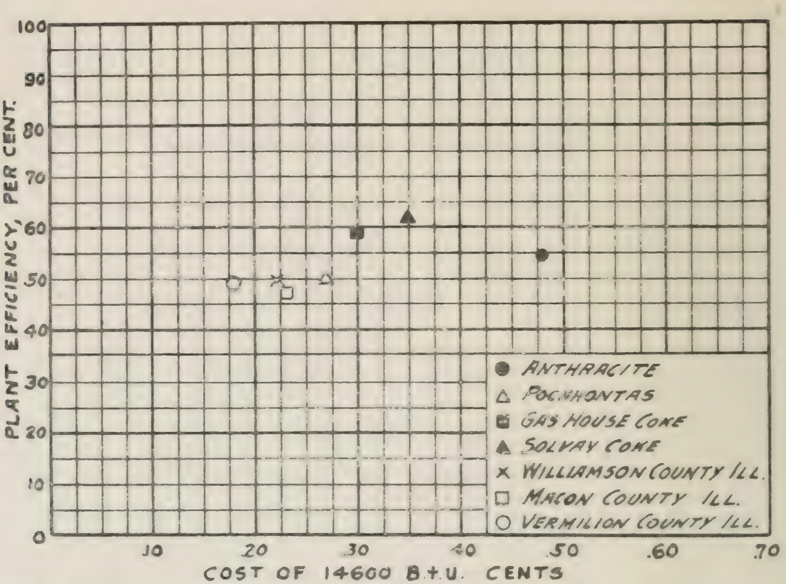

FIG. 8 RELATION BETWEEN PLANT EFFICIENCY AND COST OF 14600 B. T. U.

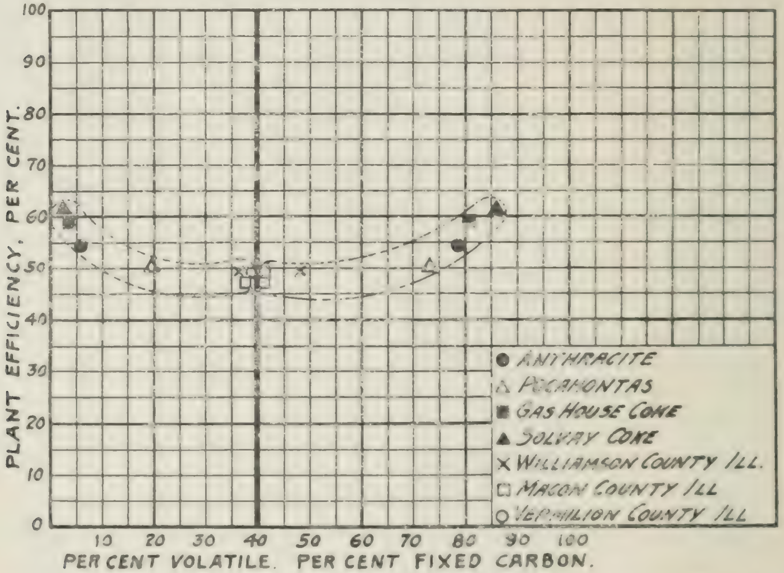

FIG. 9 RELATION OF EFFICIENCY TO PER CENT VOLATILE AND PER CENT FIXED CARBON

rated capacity. The cost of evaporating 1000 lb. of water from and at 212° F. varies from 62.37 cents for anthracite on boiler D_1 to 23.40 cents for the cheapest of the Illinois coal tested on boiler D_2. If evaporative performance alone be considered, this shows a saving of 62.5 per cent of the cost of the anthracite for the extreme cases noted. Considering each boiler separately the corresponding figures are savings of 59.7 and 56.3 per cent, respectively, in the case of boiler D_1 and boiler D_2. Similar differences as between anthracite and the other fuels, also between Illinois coals and the Pocahontas coal and the cokes, while not as great, are sufficient to warrant, other conditions being equal, the choice of Illinois coal on the ground of economy. The same percentage differences relative to fuel cost apply to the cost of serving 100 sq. ft. of radiation per hour as to the cost of evaporating 1000 lb. of water, and Column 12 merely presents in a slightly different manner the fact that as between the extreme cases of the tests considered the same heating effect was produced by one of the Illinois coals at 37.5 per cent of the fuel cost of the anthracite.

(*5*). *Relative fuel values as determined by tests.*—In Table 7 are presented relative values of the fuels tested. These values are based upon evaporative performance as determined under the test conditions and this fact should be borne in mind in comparing them. In the first part of the table the cost of evaporating 1000 lb. of water from and at 212° F. is shown for fuel prices ranging from $1.00 to $10.00 per ton for each fuel. Comparisons may be made in the following manner: if in a certain locality anthracite costs $8.00 per ton and Williamson County, Illinois, coal cost $4.00 per ton it will be seen that it will cost 56.21 cents to evaporate 1000 lb. of water with the anthracite and 31.84 cents to do the same work with the Illinois coal.

In the second part of the table the same relative values are given in a somewhat different manner. The relative values of the different fuels per ton are expressed in dollars with the price of anthracite ranging from $1.00 to $10.00 per ton. If, for example, in a given locality, anthracite costs $8.00 per ton, Williamson County, Illinois, coal is (for evaporating purposes) worth $7.03 per ton and if the Illinois coal can be bought for a less price than $7.03 a saving can be made by using it instead of the anthracite. Again, if at a certain place Williamson County coal can be purchased for $3.51 per ton then (for evaporative

TABLE 7

Relative Value of fuels for Use in House-heating Boilers as Determined by Evaporative Tests on Two Types of Boilers When Operated at 65 per cent of their Rated Capacity

Kind of Fuel	Cost in Cents of Evaporating 1000 pounds of Water from and at 212° F., with Price of Fuel Ranging from $1.00 to $10.00 per Ton of 2,000 pounds									
	$1	$2	$3	$4	$5	$6	$7	$8	$9	$10
Anthracite	7.03	14.05	21.08	28.11	35.13	42.16	49.19	56.21	63.24	70.27
Pocahontas	6.59	13.19	19.78	26.37	32.97	39.56	46.15	52.75	59.34	65.93
Gas House Coke	6.77	13.54	20.30	27.07	33.84	40.61	47.37	54.14	60.91	67.67
Solvay Coke	6.27	12.53	18.80	25.07	31.33	37.60	43.87	50.13	56.40	62.67
Illinois, Williamson county	7.96	15.92	23.88	31.84	39.80	47.76	55.72	63.68	71.64	79.60
Illinois, Macon county	9.20	18.40	27.60	36.80	46.00	55.20	64.40	73.60	82.80	92.00
Illinois, Vermilion county	8.52	17.04	25.55	34.07	42.59	51.11	59.63	68.15	76.66	85.18

Kind of Fuel	Relative Value of Fuels (Determined by Evaporative Tests) with Price Varying from $1.00 to $10.00 per Ton of 2,000 pounds of Anthracite									
	$1	$2	$3	$4	$5	$6	$7	$8	$9	$10
Anthracite	$1.00	$2.00	$3.00	$4.00	$5.00	$6.00	$7.00	$8.00	$9.00	$10.00
Pocahontas	1.07	2.14	3.21	4.28	5.35	6.42	7.49	8.56	9.63	10.70
Gas House Coke	1.04	2.07	3.12	4.15	5.19	6.23	7.27	8.31	9.35	10.39
Solvay Coke	1.12	2.23	3.34	4.46	5.58	6.69	7.81	8.92	10.04	11.15
Illinois, Williamson county	.88	1.76	2.64	3.51	4.39	5.27	6.15	7.03	7.91	8.79
Illinois, Macon county	.76	1.52	2.28	3.04	3.80	4.57	5.33	6.09	6.85	7.61
Illinois, Vermilion county	.82	1.64	2.46	3.29	4.11	4.93	5.75	6.57	7.39	8.21

purposes) anthracite is at that place only worth $4.00 per ton and if more than $4.00 must be paid for anthracite the additional amount must be considered as a loss or as being expended for advantages possessed by the anthracite such as cleanliness, and ease of fire control not possessed by the other fuel.

D. Control

Under the conditions of the tests little difficulty as to control or regulation was experienced. The observers were at all times present and gave such attention as was required to maintain the capacity desired. As already explained for these tests, questions relating to attention required, control and cleanliness were considered of secondary importance to obtaining tests comparable upon an evaporative performance basis. When burning the anthracite and the cokes, almost no attention was given the fire from one time of firing to the next. A preliminary adjustment of the chains operating the ash-pit damper and check was made for each fuel if considered necessary and was in general not changed during the tests with that fuel. It was found advisable to keep the ash-pit as nearly air tight as possible except for the damper in the ash-pit door in order that the fire might be effectually checked when the damper was closed. This was found particularly desirable in the case of the quick burning Illinois coal. In general the attention required by the Pocahontas and Illinois coals was considerably more than that required by the anthracite and coke. The regulation was also much more uniform when burning the anthracite and coke than with the other fuels.

E. Smoke

In Table 15, page 90, Appendix A, are given data relative to the smoke produced. Smoke records were not taken at all times. For the majority of the tests a record was taken for only one firing interval, that is, from the time of firing one charge of fuel to the time of making the next charge, and no data are here tabulated except such as extend over such a complete interval. Smoke records taken during the first firing interval were affected by the smoke produced by the kindling used. This is particularly marked in the case of the Solvay coke as practically no smoke was produced with this fuel after the first firing. During the time of making smoke records, observations were made at one minute intervals while smoke was being produced and at somewhat longer intervals when it was known that no smoke was being produced. The smoke produced was often of a yellow or brownish color and difficult to compare by means of the Ringelmann color scale, also owing to several changes in the personnel of observers it is not to be expected that the observations are strictly comparable. It is believed, however, that they represent fairly well the smoke conditions as nearly as that can be done by the methods employed. In making and tabulating the smoke records the Ringlemann chart numbers 1, 2, 3, 4 and 5 were considered as representing 20, 40, 60, 80 and 100 per cent black smoke respectively.

F. Cleanliness

In matters of cleanliness in and about the boiler room, the anthracite and coke were superior to the other fuels. The total ash from the Pocahontas coal was comparatively small in amount, free from clinkers and easily handled. This also was true to a somewhat less extent for the anthracite and cokes, while the ash from the Illinois coals contained more or less clinkers, was obtained in greater amount and was more troublesome to handle. Observations as to the thickness of the soot and ash collecting upon the walls of the flues were made at the end of the tests. These observations were incomplete and varied greatly as compared with each other and are not reported. For a number of the tests the soot which had collected in the flues was burned out during the tests while in other cases this did not happen. Owing to the arrangement of the flue surfaces with respect to the fire-pit this burning of the soot was much more apt to take place in boiler D_1 than in D_2.

G. General

In making fuel tests with house-heating boilers especially if it is desired to consider the boiler as well as the fuel being tested, it would seem advisable to test at approximately the average capacity at which the fuel and equipment are to be operated, or if the load demand is to be very variable, to test under conditions approximately similar to the operating conditions. If the boiler is to be used for heating purposes where the load demand will approach its rated capacity and be fairly constant over a considerable portion of the day, as might be the case in many comparatively large installations, tests under those conditions will give results as to efficiency, rate of evaporation, and other conditions which will be dependable and of value. On the other hand, tests run under conditions similar to those which might exist in a small residence, only requiring a hot fire for a few hours and an average load of possibly 20 per cent or 30 per cent of the rated capacity, would give results for the most part applicable only to like service conditions. This would necessitate tests of at least two general types, one of which would be quite similar to tests as ordinarily run upon power boilers, probably making evaporative performance the main item sought, and the other would be of the nature of a service test where much more relative attention would be paid to details concerning attendance, control, and cleanliness. Further tests which are now in progress with house-heating apparatus under various conditions as to capacity and service will, it is hoped, throw some further light upon the relations existing under widely varying service conditions.

In making a comparison of the fuels tested as to the advantages or disadvantages possessed by each, it is necessary to keep in mind the conditions under which these particular tests were made. Other test conditions as to capacity or attendance might warrant in some respects quite different conclusions.

Several general observations may, however, be made. Considering the cost factor as expressed in the cost per ton of fuel, cost per heat unit and cost per unit of evaporation, the Illinois coal has so great an advantage over anthracite or high-priced eastern coals that it seems probable that this factor alone will in a very large number of cases and to an ever increasing degree bring about the use of the cheaper fuel. This condition will come about in spite of recognized disadvantages with regard to smoke, dirt and more or less troublesome fire control, and emphasizes the necessity of perfecting conditions, fuels, or equipment, so that these drawbacks may be eliminated or reduced to a minimum. Fire conditions and general cleanliness can be bettered through proper screening and sizing of the coal, probably through washing at the mines, and through improvements made upon the fuel burning equipment. Similar care and attention to the matter of details will also to a certain extent reduce the smoke given off. At present, however, it seems unlikely that we can hope to burn Illinois coal under average domestic conditions without producing an amount of smoke which must be both unsightly and injurious. Except for a limited number of localities where effective smoke abatement laws may be operative, these conditions with respect to smoke will doubtless continue to grow worse with the increasing use of this fuel. Sufficiently decided and immediate improvement in regard to smoke prevention when burning Illinois coal in these small units is hardly to be looked for, and the remedy would seem to be rather in central station heating work or in previous preparation of the fuel to render it smokeless. Central station heating is at present only to be considered under special conditions and can not be considered as a solution of the problem as a whole. The most important and at the present time practicable method of previously preparing the fuel is through its conversion into coke. Considering cost as illustrated by the tests made it would appear that coke is still at a considerable disadvantage with respect to the raw Illinois coal, not, however, to so great an extent as anthracite. Coke has the advantages of smokelessness and cleanliness possessed by anthracite, but upon the other hand is handicapped by certain disadvantages, such as its comparative bulk, the non-suitability of a great proportion of the present heating apparatus to burn it to the best advantage, or in sufficient quantity under extreme weather conditions. Apparatus especially designed for burning coke will doubtless eliminate these difficulties to a large extent. Manufacturers of house-heating apparatus are at present offering equipment specially designed to meet this demand. Further, it is to be hoped that with the increased coke production, particularly the increased production from Illinois coal, there will come prices that will permit coke to compete favorably with the less clean fuels with respect to cost. The general use of coke as fuel for domestic purposes, and the consequent non-production of black smoke would eliminate a phase of the smoke problem which at present is both serious and difficult to handle. In a larger way also, the use of coke, as prepared for example by the Solvay or by-product process, appears to be in the direction of a solution of both the smoke problem and the problem of the economic use of the coal supply. Aside from the condition of blackness, due to unconsumed carbon, smoke contains other constituents, also injurious to both health and materials. The sulphur content, which in Illinois coal is relatively high, gives rise to one of the most injurious of such constituents. The proper preparation of Illinois coal for domestic use, whatever the process may be, should take out or reduce the quantity of injurious elements contained in the coal. The process of coal washing and the conversion of coal to coke are both beneficial in this respect and may be considered as steps in the right direction with regard to reducing the injury due both to the visible blackness of the smoke, and to the injurious constituents which occur, such as colorless gases.

In general, then, we may conclude: (1) that on the score of economy the high-priced eastern coals must give way to the cheaper home product; (2) that that product will be used in continually increasing quantities for domestic purposes; (3) that this condition will be accompanied by improved equipment and methods of burning the cheaper fuel; (4) that the use of raw Illinois coal will continue to be accompanied by a considerable amount of smoke and dirt which must eventually lead to some adequate method of preparing this fuel in order to eliminate this feature; (5) that the conversion of Illinois coal to coke offers, at present, a seemingly satisfactory method of such preparation;

and (6) that with the adaptation of equipment to satisfactorily burn coke at a price which for coke will put it on an equal footing with raw coal, coke may be expected to take a very important place as a domestic fuel, and be an important factor in its relation to the smoke problem and the fuel question as a whole.

10. *Equipment*

These tests were conducted with two house-heating boilers installed by the Engineering Experiment Station at the University of Illinois. The boilers have been designated as boiler D_1

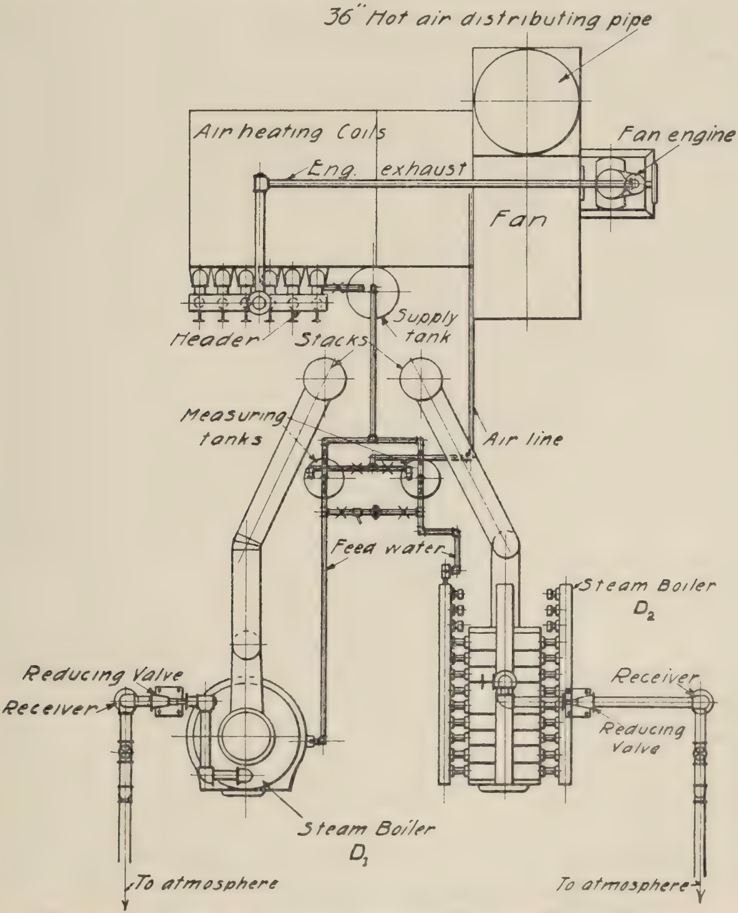

FIG. 10 PLAN OF HOUSE-HEATING BOILER TEST PLANT
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS

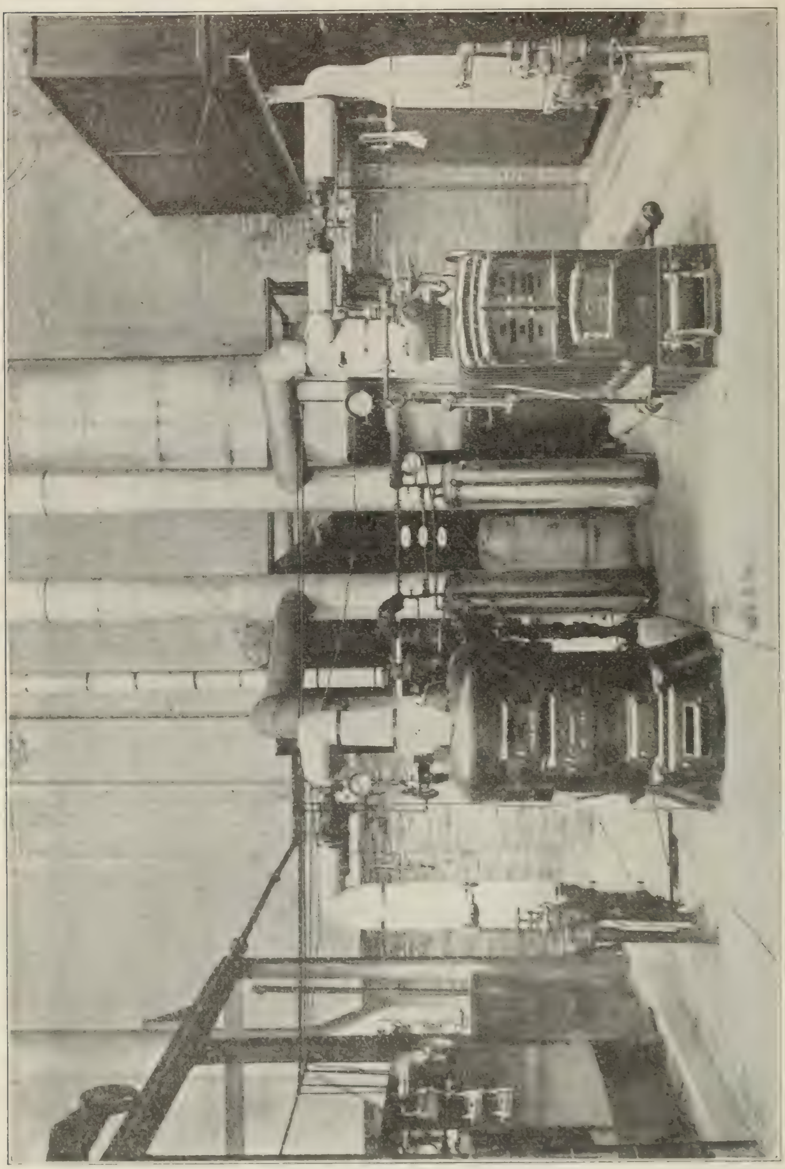

FIG. 11 GENERAL ARRANGEMENT OF PLANT

and boiler D_2. In the U. S. G. S. bulletin, which also reports the principal data and result of these tests, boilers D_1 and D_2 are referred to respectively as boilers A and B.

In Fig. 10 is shown in plan the arrangement of the plant, and in Fig. 11, from a photograph, is shown the general arrangement. The boilers are set independently, each being provided with similar load regulators, return feed water systems, and stacks. The flow is so arranged that the steam may be discharged to the atmosphere through an exhaust head above the roof of the building, or into heating coils at the rear of the boilers. These coils contain 1000 sq. ft. of radiating surface and are arranged in six sections, any number of which may be cut out, changing the amount of radiation in proportion. They form a part of the regular heating system of the laboratory.

Boiler D_1 is made up of four horizontal cast-iron sections, the base and grate section, the fire-pot, an intermediate circulation section, and the dome. Fig. 12 gives a view of the boiler erected. The water space surrounds the fire-pot, and is continued into the intermediate and dome sections through three nipples.

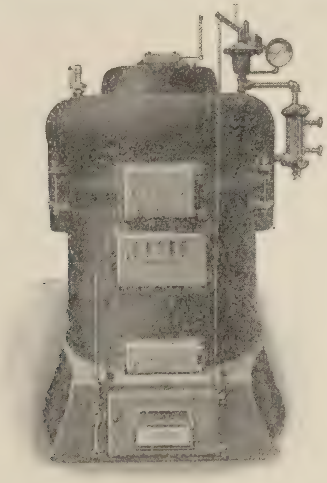

FIG. 12 BOILER D_1

The boiler upon which the tests were made is one rated at 800 sq. ft. The principal dimensions and proportions of this boiler are given in Table 8.

TABLE 8

DIMENSIONS OF BOILER D_1

Rated capacity, radiating surface	square feet	800
Height over all	feet	5½
Floor space	square feet	9
Size of fire door	inches	8½ x 15
Height of fire door above grate	inches	14
Fuel capacity to center of fire door	pounds	290
Kind of grate		plain rocking
Size of grate	inches	28 diameter
Area of grate surface	square feet	4.28
Area of air space	square feet	2.15
Ratio of air space to grate surface	per cent	50
Mean height of furnace	inches	22.5
Height of chimney above grate	feet	39
Sectional area of chimney	square feet	1.07
Area of flue connecting to chimney	square feet	.55
Length of flue connecting to chimney	feet	14
Least flue area in boiler	square feet	.67
Ratio of least flue area to grate surface	per cent	15.5
Smoke outlet above grate	feet	4.17
Kind of draft		natural
Direct water heating surface	square feet	18.8
Indirect water heating surface	square feet	20.7
Superheating surface	square feet	4.2
Total heating surface	square feet	43.7
Ratio of direct heating surface to total	per cent	43
Ratio of total heating surface to grate surface		10.2 to 1
Total water and steam space	cubic feet	7.38
Steam space	cubic feet	3.07
Water space	cubic feet	4.31
Square feet of external boiler surface in contact with water or steam		37.88

Boiler D_2 represents a type of sectional construction in which the base or grate portion and the water-heating portions are built up of interchangeable cast-iron sections, these sections or water legs being connected by means of external circulation drums or headers. Fig. 13 and 14 are respectively an assembled and a sectional view of the boiler, and give an excellent idea of the water space, gas travel, and general construction.

Fig. 13 is from a photograph of the boiler tested.

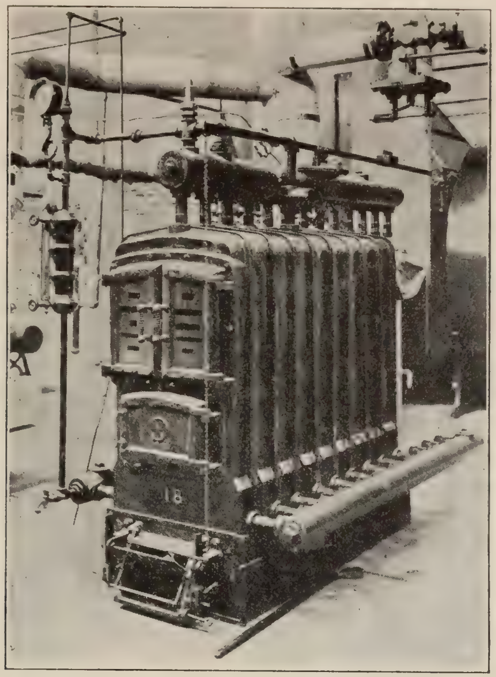

FIG. 13 BOILER D_2

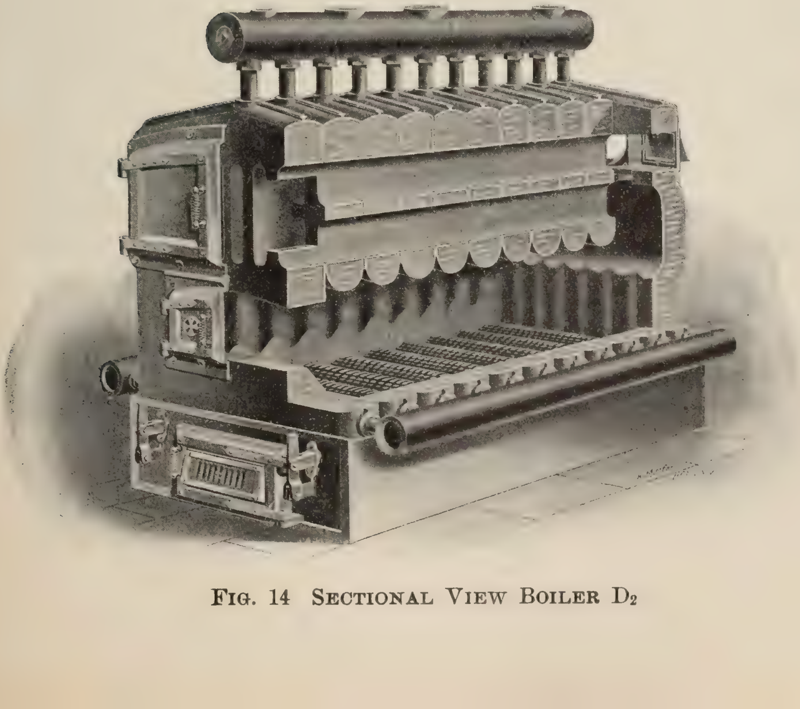

FIG. 14 SECTIONAL VIEW BOILER D_2

This type of boiler is particularly adapted to a number of experimental studies of house-heating boiler work as related to boiler proportions, on account of the ease with which such proportions may be varied. This boiler is manufactured in three widths of grate, and boilers of different capacities are obtained by combining with the different widths of grate a greater or less number of water leg and grate sections.

The boiler installed in the plant has a grate 18 in. wide, is supplied with ten intermediate sections, and with 13-hole supply and return drums, so that a number of combinations are available.

For the tests here considered the boiler consisted of nine sections. The principal dimensions and proportions are given in Table 9.

TABLE 9

DIMENSIONS OF BOILER D_2

Rated capacity, radiating surface......	square feet	1075
Height over all........................	feet	5¾
Floor space............................	square feet	25
Size of fire door......................	inches	9 x 15
Height of bottom of fire door above grate	inches	10
Fuel capacity to center of fire door.....	pounds	370
Kind of grate..........................		patent rocker
Width of grate.........................	inches	18
Length of grate........................	inches	48
Area of grate surface..................	square feet	6.0
Area of air space......................	square feet	3.0
Ratios of air space to grate surface....	per cent	50
Mean height of furnace.................	inches	22
Height of chimney above grate..........	feet	39
Diameter of flue.......................	inches	14
Sectional area of chimney..............	square feet	1.07
Area of flue connecting to chimney	square feet	.55
Length of flue connecting to chimney..	feet	12½
Least flue area in boiler..............	square feet	.495
Ratio of least flue area to grate surface	per cent	8.23
Smoke outlet above grate...............	feet	3.0
Kind of draft		natural
Direct water heating surface...........	square feet	21.89

Indirect water heating surface	square feet	53.98
Superheating surface		none
Total heating surface	square feet	75.87
Ratio of direct heating surface to total	per cent	28.9
Ratio of total heating surface to grate surface		12.6 to 1
Total water and steam space	cubic feet	11.16
Steam space	cubic feet	3.28
Water space	cubic feet	7.88
Square feet of external boiler surface in contact with water or steam	square feet	103.27

(1) *Feed water system.*—The adoption of the arrangement here described, in which the feed water is forced from the measuring tanks into the boiler by means of compressed air, was influenced to some degree by the desire to use condensation water from the heating coils, noted on page 47. It has, however, proved very satisfactory, requiring little attention, and is convenient, since all of the apparatus is located upon the same level and within easy range for the observer. The arrangement of this apparatus is shown in Fig. 10 and 11, pages 45 and 46. The tanks are ordinary galvanized iron range tanks. One supply tank of fifty-four gallons is connected directly in the return from the heating coils. The inlet pipe passes to the bottom of the tank, and the outlet is at the top so that the tank is at all times filled with hot water.

The measuring tanks, or feed tanks, one for each boiler, 35 gallons capacity, are fitted with gage glasses and scales graduated to read pounds direct, correction being made for varying temperatures. An overflow pipe, with valve, located at the top of the scale, allows filling the tank with a definite charge of water.

These tanks, as stated above, are connected with the laboratory compressed air system, and during feeding are under pressure sufficient to force the water into the boilers. A $\frac{1}{2}$-in. needle valve near the boiler allows close regulation of the feed. The heating system is under three to five pounds pressure, so that the measuring tanks can be filled by simply opening a valve leading to the supply tank. The measuring tanks can be filled somewhat more rapidly if it is desired, by means of compressed air, suitable connections being in place. The air pressure and boiler are cut off from the measuring tanks and the overflow opened during charging.

(2). *Load regulator and separator.*—Since these small heating boilers are designed to regulate themselves, under control of their automatic damper regulators, the rate of combustion may be kept fairly regular by keeping the rate of evaporation constant. This has been accomplished by the use of a pressure regulator, by means of which a steady flow of steam is discharged from a constant pressure receiver through a suitable orifice into the atmosphere, provision being made for varying the load to suit the specific demand of the test.

The receivers perform the duty of separators and are thus used to replace the usual steam calorimeter, for which reason the receivers and pipes are heavily lagged with hair felt and pipe covering, one inch of felt being first laid next to the iron and above this a one-inch thickness of magnesia pipe covering. The regulators are shown to the right and left of the boilers in Fig. 11, page 46.

Fig. 15 shows one of the load regulators with its covering removed. The steam from the boiler passes through the pressure regulator *A* into a 3-inch pipe, which extends through the top of the receiver and nearly to the reducing tee at the bottom. Here the direction of steam is changed and entrained moisture separated, the dry steam passing up and out through *F* and to the exhaust main *J*, through an orifice plate in the 2-inch union *G*, the pipe *J* being open to the atmosphere. Difference of pressure as between the receiver and on the exhaust side of the orifice plate as at *J*, is indicated by a mercury manometer at *C* made up with suitable connections. A slight back pressure due to friction usually existed in pipe *J*. No attempt was made to compute the evaporation in this manner. The moisture separated from the steam collects in the 3-inch trap *D*, the amount of which is indicated in pounds and fractions on the gage glass. Some moisture originally in the steam is, doubtless, evaporated in passing the reducing valve, consequently correction of computed results for quality of steam and conversion to equivalent evaporation from and at 212° are made on the basis of the mean pressure maintained in the receiver, which is usually about two pounds.

Variation in load is obtained by the introduction of suitable orifices at *G*. The by-pass valve *E*, allows changes to be made during operation, the orifices taking the place of a gasket in the union.

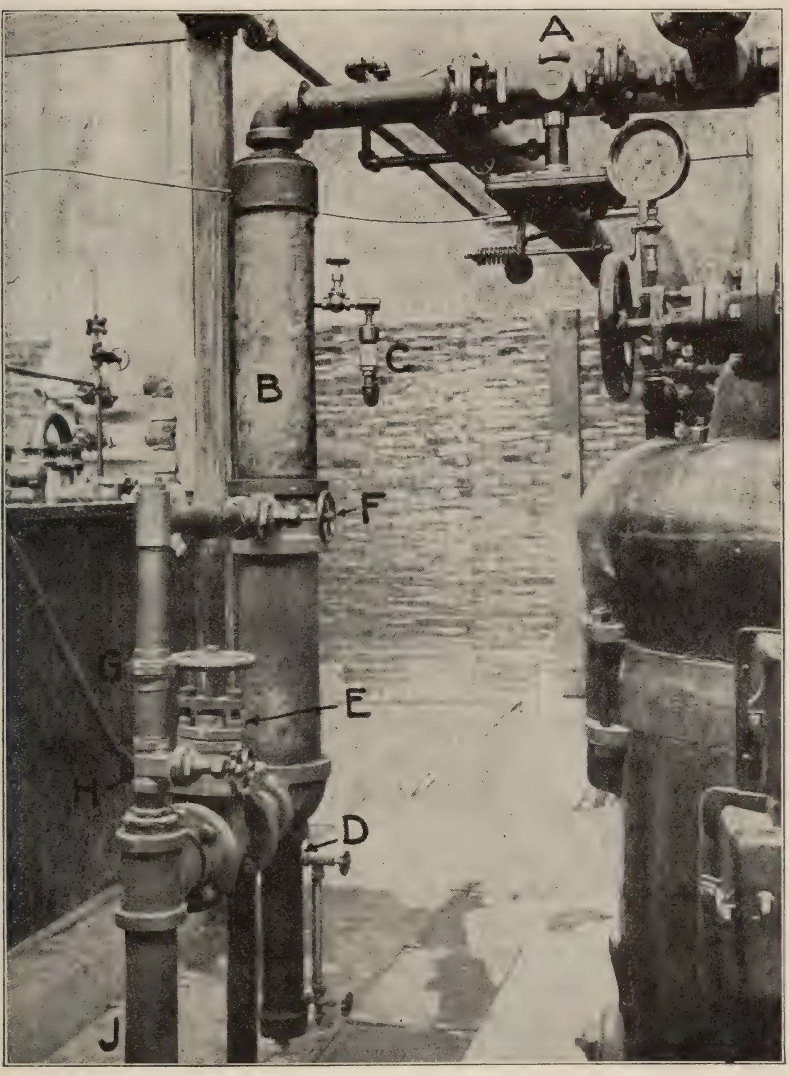

FIG. 15 LOAD REGULATOR

II. Fuel Tests with House heating Boilers made by the United States Geological Survey

(58 tests: 47 with briquetted fuel; 11 with raw fuel).

11. *Introduction*

As has been stated already the material presented in Part II was almost entirely supplied through the courtesy of the Technologic Branch of the U. S. G. S. These tests are more fully reported in bulletin No. 366 by the U. S. G. S.

Beginning in October, 1906, a number of evaporative tests were made at St. Louis, Missouri, under the direction of the United States Geological Survey, on the house-heating boiler installed to heat the buildings occupied by the Structural Materials Testing Division. 58 such tests were made; 11 tests were made with raw coal and 47 with briquetted coal having a binder of pitch.

12. *Summary and Conclusions*

The briquets and coal burned on the tests at St. Louis came from eleven states or territories. There were 58 tests, 11 on raw coals, 34 on round briquets and 13 on square briquets. Most tests ran about 8 hours and carried an average steam pressure of from 2 to 3 lb. The amount of fuel fired at each firing varied from 55 to 175 lb. The interval between firings varied considerably; on some tests coal was fired every half hour and on others every two hours. The average efficiency of all of the tests was 51.48; it varied from 38.67 on an Illinois coal to 65.36 on a Virginia coal. The average per cent of builders' rated capacity developed was 59.2. It ranged from 44 per cent on an Illinois coal to 77.2 on an Indian Territory coal. The lowest boiler horse-power developed was 12.1 and the highest 20.6. With fuel at $1.00 per 2000 lb., the cost of evaporating 1000 lb. of water from and at 212° F. varied from 5.56 cents for a Pennsylvania coal briquetted to 11.93 cents for an Illinois coal briquetted.

Most of the briquets, whether made from eastern or western coal, smoked badly for several minutes after firing. Of the coal tested raw, 6 were on western and 5 on eastern coal. The high volatile western coals smoked badly, but the eastern coals made comparatively little smoke.

13. *Fuel*

Table 10 gives a description of the coal and binders used in the briquets tested. Further information relative to the coal tested and to the binders employed has been published in the bulletins of the U. S. G. S.* The chemical properties of these fuels as shown by proximate and ultimate analyses are contained in Table 16, on page 94, Appendix B.

On comparing the results of tests on the coal and briquets there seems to be no advantage in the briquets over coal of a suitable size for house boiler heating. Briquetting a good bituminous coal would be justified when slack is used for material and the gain would be due almost entirely to the more favorable size of the fuel. This gain is less for coals which coke readily than for non-coking coals which are not suitable for domestic purposes in the form of slack. Briquets made from such coal burn fairly well, as they allow the air to pass up through the fuel bed.

These experiments have shown that the pitch binders used are not suitable for a furnace working at the low temperatures common in a house-heating boiler, as they volatilized and in most cases escaped unburned or were deposited on the surface of the boiler. This coating generally burned off once or twice a day, causing a high temperature in the flue, and, as a consequence, danger from fire.

14. *Methods of Conducting Tests*

The tests were made to conform as nearly as possible to actual running conditions of the average house-heating boiler plant. Steam was supplied to two buildings for heating and consequently the load varied with the weather, according to both the temperature of the outside air and velocity of the wind. On only a few of the tests was the heating load so light that steam was turned into the atmosphere.

The tests usually covered a period of about eight hours; during this time the operator tried to maintain a steam pressure of about three pounds. The alternate method, as prescribed by the A. S. M. E. code for making boiler trials, was used in starting and stopping the tests. The boiler was installed in so small a

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* Bulletin 332, Report U. S. Fuel Testing Plant 1906-7.
Bulletin 261, Preliminary Report on Coal Testing Plant.
Bulletin 343, Binders for coal briquets.

TABLE 10 Coal and Binders used in Briquets

Coal				Binder [a]			
Field Designation	Locality	County	Shape of Briquet	Percentage Used	Flowing Point	Oils by Distillation up to 743° F.	Extraction analysis: Pitch extracted (sample as received) by CS_2
					° *F.*	*Per ct.*	*Per cent*
Arkansas No. 13	Denning	Franklin	Round	7	140.0	34.44	95.20
Illinois:							
No. 7 E	Near Collinsville	Madison	"	8	143.6	25.76	96.90
No. 9 C	Near Staunton	Macoupin	"	9	143.6	25.76	96.90
No. 12 B W	Bush	Williamson	Square	6.25	143.6	39.05	99.66
No. 29 A W	Livingston	Madison	Round	7	143.6	39.05	99.66
No. 29 B	"	"	"	7	143.6	39.05	99.66
No. 30 W	Shiloh	St. Clair	"	8.5	143.6	25.76	96.90
No. 31	Warden	"	"	8	143.6	25.76	96.90
No. 31	"	"	Square	7	161.6	28.98	89.31
No. 33	Trenton	Clinton	Round	8	143.6	25.76	96.90
Indiana:							
No. 1 B	Mildred	Sullivan	"	8.5	161.6	28.98	89.31
No. 5 B	Hymera	"	"	9	143.6	25.76	96.90
No. 6 B	"	"	"	8.5	143.6	25.76	96.90
No. 6 B	"	"	Square	7	143.6	25.76	96.90
Indian Territory:							
No. 2 B	Hartshorne		Round	8	186.8	24.70	85.57
No. 2 B	"		Square	8	172.4	20.00	99.60
Kansas:							
No. 2 B	Yale	Crawford	Round	7	143.6	39.05	99.66
No. 2 B	"	"	Square	7	143.6	39.05	99.66
Maryland No. 2	Frostburg	Allegheny	Round	8	143.6	25.76	96.90
Missouri No. 10	Bevier	Macon	"	8	143.6	39.05	99.66
Pennsylvania:							
No. 18	Lloydell	Cambria	"	8	143.6	25.76	96.90
No. 18	"	"	Square	7 [b]8	143.6 114.8	25.76 5.76	96.90 100.00
No. 19	Herminie	Westmoreland	Round	8	143.6	25.76	96.90
No. 20	Near Seward	"	Square	6	161.6	28.98	89.31
No. 20 W	"	"	Round	8	161.6	28.98	89.31
No. 22	Huff	"	"	7	161.6	28.98	89.31
No. 22	"	"	Square	6	161.6	28.98	89.31
Pennsylvania No. 15 (one-fourth).	Wehrum	Indiana	Round	6.25	143.6	39.05	99.66
Rhode Island No. 1 (three-fourths).	Cranston	Providence					
Pennsylvania No. 18 (one-fourth).	Lloydell	Cambria	"	8	143.6	25.76	96.90
Miscellaneous No. 9 (three-fourths).							
Pennsylvania No. 18 (one-half).	Lloydell	Cambria	"	8	156.2	25.47	90.56
Rhode Island No. 1 (one-half).	Cranston	Providence					
Pennsylvania No. 18 (three-fourths).	Lloydell	Cambria	"	8	143.6	25.76	96.90
Miscellaneous No. 9 (one-fourth).							
Pennsylvania No. 18 (one-half).	Lloydell	Cambria	"	8	143.6	25.76	96.90
Miscellaneous No. 9 (one-half).							
Virginia No. 5 B	10 miles west of Blacksburg	Montgomery	"	7	143.6	39.05	99.66

[a] Water-gas pitch except where otherwise noted.

[b] Wax tailings.

room that the standard method of starting and stopping the tests was not practicable.

Each test was started with a fire about 4 in. thick. This thickness was gradually increased, varying from 12 to 18 in. depending upon the kind of coal burned and upon the judgment of the operator as to the best thickness for good combustion. To start a test with a 4-in. fuel bed required that the same coal used on the test must be fired for about four hours before the start of the test. To build up the fire required light firings at first and the same procedure was followed to burn it down for a close. At other times during the tests the amount of coal fired was considerably greater. Coal was fired whenever the heat requirements demanded it, usually at a time when the fire had burned down and the steam pressure had dropped. When the coal was fired it was spread over the entire fuel bed. The fire seldom required any attention and it was never poked unless a coal was being burned that coked badly. On the tests the fire was cleaned only just before starting and stopping, except in two or three cases when there was an unusually large accumulation of clinker upon the grate.

Readings were taken of draft, temperature and steam pressure, every 30 minutes. Smoke readings were taken as soon after coal was fired as other observations would permit and it was observed at intervals until the volatile matter had been driven off and no smoke was given off from the stack.

Owing to the many duties of the observer there was difficulty in securing and analyzing representative samples of flue gas, but the results are considered of sufficient accuracy to indicate certain general relations between the air supply and the performance of the boiler.

All gas samples analyzed gave some CO in the flue gas. This was to be expected as the combustion was never complete on any of the tests as evidenced by watching the top of the stack.

Observations showed the smoke black at times of firing and comparable with the Ringelmann charts, gradually turning gray after several minutes. This is of interest owing to the fact that the gases resulting from the combustion of briquets at the Illinois Engineering Experiment Station were usually of a dirty yellowish color and not comparable with the usual standard.

All briquets were fired whole. Shortly after they were fired distillation of the tar took place and condensed on the boiler surface, forming a covering over the flue passages. When the fire was allowed to burn freely the coating on flues ignited. This often happened two or three times during an eight hour run and would increase the temperature in the flues as high as 1500° F. On this account a thermo-couple was used to take the temperature of the stack gases.

The furnace door was opened only at times of firing. An attempt was made on a few special briquet tests to reduce the smoke after firings by opening the slide draft in the furnace door, but either there was not enough air or it was admitted at the wrong point for there was no appreciable reduction of smoke. No attempt was ever made to introduce air over the fire on the regular series of tests.

The flue passages were not brushed during the tests with briquets as the burning of the tar effectually cleaned the boiler surfaces. In some cases the tar coating without doubt greatly lowered the efficiency of the boiler. It will be noted that the raw coal gave better results than when briquetted.

The analyses of the fuel burned and of the refuse were made at the chemical laboratory of the fuel testing plant.

15. *Data and Results*

In Table 16, pages 92 to 98, Appendix B, will be found the principal data and results relative to these tests. Table 17, page 99, gives the average per cent of CO_2, O_2 and CO for 52 of the tests.

16. *Equipment*

Fig. 16 and 17, pages 59 and 60 show plan and elevation drawings of the house-heating boiler plant as tested at St. Louis.

The boiler on which these tests were made is of the sectional type. It contains seven separate sections, measures 66 in. in length, has a grate 36 x 54⅛ in., three 5-in. steam outlets at the top of the sections and is rated to take care of 3150 sq. ft. of radiating surface.

The boiler furnished steam to two buildings, supplying the necessary amount through two of the three outlets. The front outlet was not in use and was capped over. This boiler is made so that feed water may be supplied to every other section. It enters at the base of the section on both sides just above the grate level. There are six return inlets, but in this installation

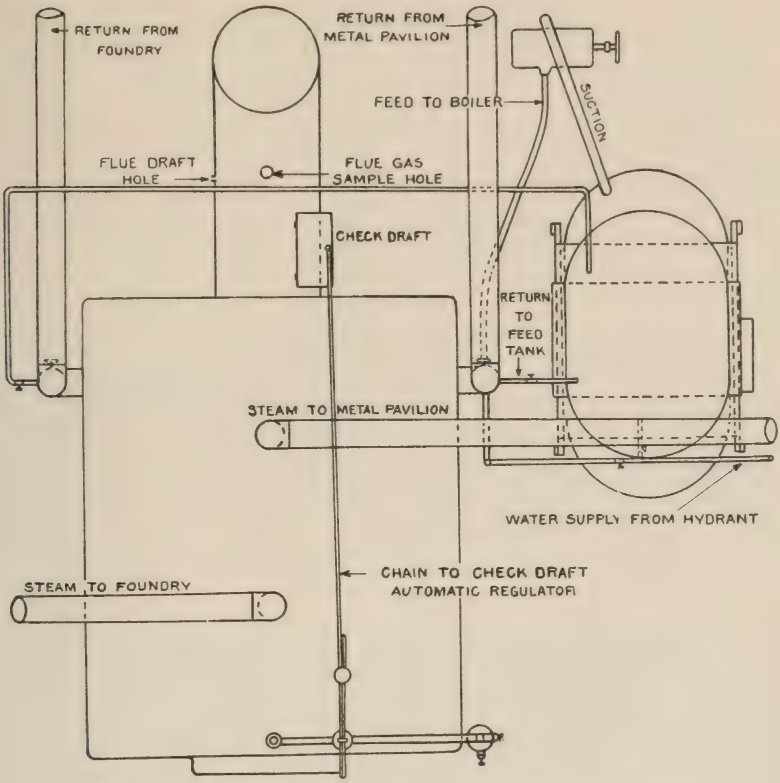

FIG. 16 PLAN OF HOUSE-HEATING BOILER PLANT AT ST. LOUIS, MO.

only the rear two were used. The piping was so arranged that during a test period all of the condensation was returned to a weighing tank, then allowed to discharge into a supply tank from which it was forced into the boiler by means of a hand pump. The temperature of the water entering the boiler varied from 100° to 150° F., but usually averaged 140° F. During a test all the water entered the boiler through one of the rear inlet openings.

A sectional boiler is usually installed so that the steam as it is taken from the sections is first drawn into a collecting drum, so that water will not be carried into the pipes with the steam in case of a sudden demand for steam. There was not enough head room for the installation of this drum at the St. Louis plant and the steam was drawn directly from two sections. Drain pipes con-

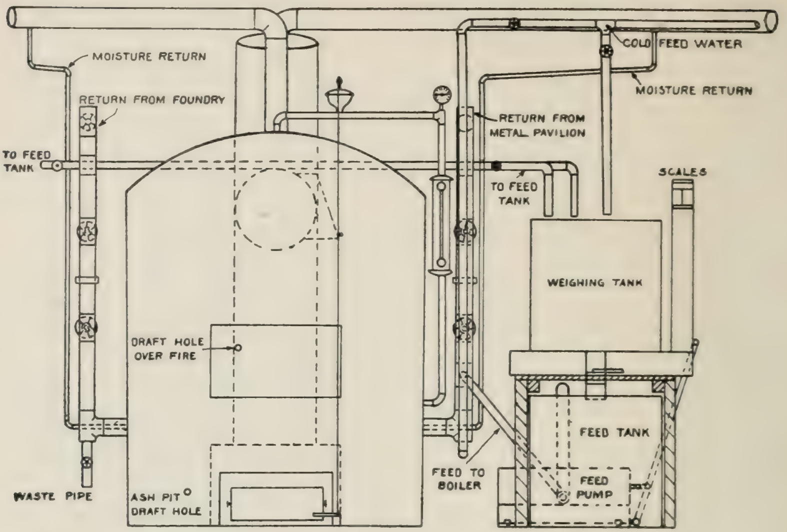

FIG. 17 ELEVATION OF HOUSE-HEATING BOILER PLANT AT ST. LOUIS, MO.

nected with the bottom of the steam pipes, as shown in the drawing, carried moisture back to the boiler. No moisture readings were made on the steam; therefore, in making calculations on the amount of water evaporated, the moisture was not accounted for and the boiler has been credited with slightly more work than it performed.

A siphon damper regulator was used to control the draft through the fire so that a nearly constant steam pressure might be carried. This regulator was connected direct to the lower check also by an arrangement of pulleys to the check in the flue.

On the first 30 tests the draft was supplied by a stack 32.4 ft. above the grate. On these tests both natural and induced draft were used. On the last 28 tests the stack was raised to 44.8 ft. above the grate level. This height of stack always furnished the required amount of draft.

All except the front of the boiler was lagged with about an inch covering of plastic asbestos.

III. FUEL TESTS WITH HOUSE-HEATING BOILERS MADE BY THE ENGINEERING EXPERIMENT STATION

(24 tests with briquetted fuel)

17. *Introduction*

24 tests were made when burning briquetted fuel in connection with house-heating boilers by the Engineering Experiment Station of the University of Illinois during the months of June and July, 1907. The tests described in Part II of this article made by the U. S. G.S., at St. Louis, led to the desire to conduct additional tests under more constant conditions than could be maintained at the St. Louis plant.

18. *Summary*

An average capacity of 65 per cent was carried on all of the 24 tests, the variation being from 53.2 to 71.4 per cent. The boiler horse-power developed on boiler D_1 ranged from 4.52 to 4.96; on boiler D_2 from 4.97 to 6.16. The average efficiency of the boiler and furnace, figured on a dry coal basis, gave 44.85 per cent for the 24 tests. Comparing 8 tests on briquets, 4 of which were made on large briquets and 4 on small briquets, it is shown that in every case the large briquets gave an appreciably higher efficiency showing that the size of the coal burned is an important factor. With fuel at $1.00 per 2000 lb., the cost of evaporating 1000 lb. of water from and at 212° F., varied from 6.74 cents on a Pennsylvania briquet test to 12.47 cents on an Illinois test.

The briquets started readily from a wood fire and burned well, but owing to the difficulty of obtaining complete combustion, the average efficiency from an 8 hour test was low. The formation of soot in the flues of boiler D_2 was more troublesome than in boiler D_1. In two instances the flues of boiler D_2 were completely stopped up after an 8-hour run.

To carry only 65 per cent of the rated radiating surface the draft through the fire was either cut off or very nearly so for one-half to three-quarters of the time.

19. *Fuel*

A carload of briquets was shipped to the Engineering Experiment Station at Urbana, Illinois, and the results here recorded are from tests made with this fuel. The briquets were manufactured at the U. S. G. S. fuel testing plant and were of two sizes and shapes. The round briquets were 3⅛ in. in diameter and 2 in. thick. The square briquets were 4¼ in. x 6¾ in. x 2½ in. 24 tests were made, twelve on each of two boilers. 18 of the tests were on round briquets manufactured with the Renfrow briquetting machine, the other six with square briquets made on the English briquetting machine. These machines and their products have been described in the bulletins issued by the U. S. G. S., concerning the fuel testing plant at St. Louis.* The square briquets were broken in halves before firing. The percentages of pitch in the briquets varied from 7 per cent to 8 per cent. The chemical properties of these fuels as to moisture and ash are given in Table 18, page 104, Appendix C.

20. *Methods of Conducting Tests*

The methods employed in conducting the tests were also in general the same as those used in making the tests considered in Part I and have been described in connection with those tests under the heading "Methods of Conducting Tests" upon pages 15 to 20 inclusive. For the tests here considered the following are the principal conditions under which they were planned to be run.

(*1*). The load to be maintained between 60 and 70 per cent of the builders' rated capacity.

(*2*). The load to be uniform throughout the test.

(*3*). A steam pressure of 2 lb. to be carried on the heating system.

(*4*). A definite charge of coal to be supplied at each firing.

(*5*). Each test to be of approximately 8 hours' duration.

The air supply was taken entirely through the ash-pit door. On some of the tests it might have been advisable to continuously admit a part of the air used for combustion over the fire through the furnace door or it might have been possible to have increased the over-all efficiency of the boiler by admitting air

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*Professional Paper No. 48, Part III.
Bulletin 261. Preliminary Report on Coal Testing Plant.
Bulletin 290. Operations of Fuel Testing Plant in 1905.
Bulletin 332. Report U. S. Fuel Testing Plant, 1906-7.
Bulletin 343. Binders for Coal Briquets.

over the fire for a few minutes after each firing by cracking the furnace door; however, since this is not commercially practicable, no attempt was made to prove or disprove the statement.

The boiler flues were blown after the close of every test, so that the heat developed on each of the tests had an equal chance on the heating surface at the start of the test; however, on some of the trials more soot was formed than on others, which made the heating surface on these trials much less effective at the close of the test than at the start.

The standard method of the A. S. M. E. code for conducting boiler trials was employed, the test being started when the wood was lighted. As soon as the wood was burning well, about 25 lb. of the fuel was fired. In about 8 or 10 minutes, the remainder of a 75-lb. charge of fuel was fired.

Observations concerning temperatures, pressures, drafts and water measurements were recorded every 15 minutes.

As the duration of the trials was to be approximately 8 hours, just enough coal was put on the fire at the last firing to keep up 5 pounds steam pressure until time to close the test.

21. *Data and Results*

In Table 18, pages 102 to 108, Appendix C, will be found the principal data and results relative to these tests.

(*1*). *Soot*—Table 11, below, shows the amount and character of soot found on flues of boilers D_1 and D_2 as determined and recorded at the end of test. Measurements were taken in the flues of the boiler.

TABLE 11

AMOUNT AND CHARACTER OF SOOT FORMED IN FLUES

Test No.	Boiler	Soot Measurements	Test No.	Boiler	Soot Measurements
136	D_1		140	D_1	Heavy; ⅛ inch thick
137	D_2		141	D_2	Heavy; ⅛ inch to ¼ inch thick.
152	D_1	Heavy: 1-16 inch to ⅛ inch thick	146	D_1	Heavy: large amount.
153	D_2	Heavy; 1-16 inch to ⅛ inch thick.	147	D_2	Large amount; choked draft entirely off.
154	D_1	Light and fluffy; ⅛ inch thick.	148	D_1	1-16 inch to ⅛ inch thick.
155	D_2	Light and fluffy; ¾ inch thick. Choked draft entirely off.	149	D_2	Heavy; large amount.
142	D_1	Heavy.	138	D_1	Very little.
143	D_2	Heavy.	139	D_2	Very little.
144	D_1	Heavy.	156	D_1	Fine and heavy; small amount.
145	D_2	Heavy.	157	D_2	Very little.
158	D_1	Very little.	150	D_1	1-16 inch thick or less.
159	D_2	Flaky; ¼ inch thick.	151	D_2	1-16 inch thick or less.

Owing to the fact that the character of the soot was so variable, it is difficult to draw any conclusion on comparative thickness of soot. The above table shows that there was a big variation in the amount of soot formed. It is noticeable that on several of the tests a great deal of soot lodged in the flues and in a few instances the flues were filled, choking the draft off entirely. More difficulty was experienced with soot on Boiler D_2 than on D_1.

(2). *Smoke*—The smoke observations for the tests made at the Illinois Engineering Experiment Station are not reported owing to the uncertainty of comparative accuracy. The readings were extremely difficult to estimate, due largely to the peculiar color of the smoke. Smoke of about a shade between Ringelmann No. 1 and No. 2, from briquets made with pitch binder, is of a dirty yellowish color and far more offensive than No. 4 smoke from raw or washed coal, and probably would be of about the same gravimetric density as the No. 4 smoke from coal. On all briquet tests, the stack smoked badly for three-quarters of an hour after firing. After about one hour after firing the stack was almost clean, remaining so until another charge was fired.

22. *Equipment*

The equipment used in making these tests consisted of the two house-heating boilers installed by the Engineering Experiment Station of the University of Illinois and designated as boiler D_1 and boiler D_2. Except for a few minor changes in regard to the type or arrangement of the apparatus used in making observations, the equipment and its arrangement are the same as employed when making the 48 tests considered in Part I of this bulletin. Description of this equipment has already been given and will be found upon pages 45 to 53, inclusive.

APPENDIX A

APPENDIX A

23. *Tabulated Results*

The principal data and calculated results of the 48 tests are given in Table 12, on pages 70 to 83. The column heading numbers ranging from 1 upon page 70 to 73 upon page 82, correspond to the item numbers upon a final report sheet which was worked up for each test, and in general are arranged in much the same order as corresponding items in the A. S. M. E code for boiler trials.

The first three columns upon each page of Table 12 are the same, and serve as a guide in showing the connection throughout the different pages. These columns give the laboratory test number, the boiler operated and the kind of fuel used.

Upon page 70 are given the date upon which the test was made, the length of the test in hours, and average values of steam pressures, drafts and temperatures. The average steam pressures are in no case recorded closer than to the nearest half pound. The manometer on the receiver, being connected to give the difference in pressure between the two sides of the orifice, did not indicate the true pressure in the receiver. The pressure on the exhaust side of the orifice plate was, however, so small as not to make the average pressure higher than 2 lb. as recorded above. It will be noted that in one test the average pressure in the receiver was 1.5 lb.

The draft in the ashpit was taken along with other observations at regular 20 minute intervals. Owing to the fact that at the time of taking such observations the damper to the ash-pit might be in any position from tightly closed to wide open, an average of such readings would be of little or no value and has been omitted from the tabulated results. In general the draft in the ash-pit varied from practically zero when the ash door opening was wide open, to approximately the same draft as existed over the fire when the damper was closed. A record of the position of the ash door damper and the smoke pipe check was kept in connection with the observations made upon drafts.

Pages 72 and 75 contain information relative to the fuel. Items 20, 21 and 21.1 show the amount of moist fuel fired while item 21.2 shows the same as corrected on account of the residual fuel drawn at the end of the test. Items 23 and 23.1 show the amount of fuel expressed as dry or moisture-free fuel. Item 23.2 gives the amount of dry fuel actually consumed, further correction having been made allowing for the unburned fuel removed with the ash. Items 24 and 25 exhibit respectively the ash and residual fuel which were obtained for each test. Items 37 and 38, page 76 give the analyses of the residual fuel as divided into carbon and earthy matter, while items 40 and 41 give corresponding information relative to the ash. Items 45 and 46 give the calorific value for the fuel used in each test expressed upon both a dry fuel and upon a fuel as fired basis. Items 43 and 44 exhibit the average rate of combustion maintained, expressed as dry fuel per hour and as dry fuel per square foot of grate surface per hour.

Upon page 74 are given the proximate analyses of the fuel for each test with the items expressed in per cent of fuel as fired and moisture-free coal. This table has already been referred to in the sections concerning fuel and methods.

Page 78 presents information relative to the water evaporated. Item 47 gives the moisture in the steam as determined in the receiver. The steam from the boiler to the receiver was probably dried to a considerable extent in passing the reducing valve and a part of the moisture collected in the receiver is due to condensation rather than entrained moisture. The moisture as here recorded is not a measure of the dryness of the steam as generated by the boiler at boiler pressure. It has, however, been used in the calculations for determining boiler performance as the moisture in the steam when reduced to receiver pressure. It will be noted that the moisture content so determined is comparatively small and the corresponding corrections of little effect in the final determinations regarding evaporative performance. Items 49, 50 and 52 give the amount of water fed to the boiler, the same corrected for quality of steam to give the amount evaporated and the equivalent evaporation from and at 212° F. Items 53 and 54 give operating conditions with reference to water evaporated, showing the total equivalent evaporation per hour and the same per square foot of heating-surface per hour. Items 48 and 51 are factors used in calculating other items listed on the table.

Upon page 80 are given results relative to the load carried. As already stated, the attempt was made to run at a load equal to approximately 65 per cent of the boiler rating. An examination of the per cent given under item 56 shows that the highest capacity recorded for any test was 71.25 per cent and the lowest 58.33 per cent, the remainder of the values ranging between these two. Item 55 gives the load expressed in square feet of radiation served. For the purpose of calculating this load an evaporation of 0.3 lb. of water from and at 212° F. was considered equivalent to serving one square foot of radiation for one hour. Table 8 shows that of the external boiler surface of boiler D_1, 37.88 sq.ft. was on the inner side in contact with steam and water, and Table 9 shows that 103 27 sq. ft. of the surface of boiler D_2 was under similar conditions. This surface could be considered radiating surface and if added to the surface served as shown by item 55 would increase the load and show the boiler operating at a somewhat higher capacity than is shown by item 56, which is based upon evaporation only, without regard to radiation loss from the boiler. Item 55.1 shows the load carried when this boiler radiating surface is added to the load as calculated from evaporative performance. It is inserted here in order to call attention to the very considerable difference which such an assumption would make, but is not otherwise used in any of the calculations involving capacity, item 55 being used for that purpose. It was not considered advisable to make use of item 55.1 owing to the uncertainty as to how closely a square foot of the boiler radiating surface might be considered equivalent to a square foot of radiation as defined above, and especially on account of the fact that house-heating boilers in service may not be lagged and their exposed surface is rarely considered in estimating the radiating surface served. In case the boilers under consideration were lagged a portion only of the heat lost by radiation could have been utilized in evaporating water.

Items 57 and 58 give the equivalent evaporation per pound of fuel. Items 59 and 60 give the fuel consumed per hour per 100 sq. ft. of radiation, expressed in fuel as fired and in dry fuel.

Items 61 and 62, page 82, give efficiencies as calculated in the usual manner. Item 61 gives the efficiency when only the boiler and furnace are considered. Item 62 gives the plant efficiency, that is, the efficiency of the boiler, furnace and grate. The same grates were used thoughout and the efficiency of boiler and furnace without grate differs from the efficiency with grate only on account of the unconsumed fuel which passed through the grate. The grates may have been more suitable for the retention of some of the fuels than of others. In so far as the grate serves as a part of the furnace, as in the matter of air supply, its effect is of course included in both efficiencies.

Items 64 and 65 give the cost of serving 100 sq. ft. of radiation and of evaporating 1000 lb. of water from and at 212° F. based upon an assumed fuel cost of $1.00 per ton of 2000 lb.

Items 70, 71, 72 and 73 give a number of the conditions which prevailed with respect to fire conditions. Item 70 (fuel fired at each firing) shows that 75 and 105 lb. of fuel constituted the firing charge for boilers D_1 and D_2, respectively. The first fire of each test, however, consisted of this amount of fuel and a sufficient weight of white pine kindling to ignite it. From 15 to 25 lb. of kindling were used in this manner upon each test. In all calculations involving fuel this kindling was allowed for on the basis of 1 lb. of wood being equivalent to 0.4 lb. of the fuel employed.

In calculating item 72 (average interval between times in shaking and raking) each firing was considered as a time of shaking and raking, whether the fire was touched or not, other than to put on fresh fuel, also poking, leveling, or other working of the fire was so considered. Where the average interval between times of shaking and raking is the same as the average interval between firings (item 71) the fire was not touched between firings throughout the test.

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA[1]

Test Number	Boiler	Kind of Fuel	Date 1908	Duration of Test (hours)	Average Pressures				Average Temperatures (°F)		
					Steam [Gage] pounds		Draft (in. of water)		Boiler Room	Feed Water	Flue Gas
					Boiler	Receiver	Flue	Over Fire			
				1	10	11	12	13	15	16	17
162	D1	Anthracite	February 24	8.77	5.0	2.0	.13	.10	83	171	585
166	....		March 2	16.55	4.5	2 0	.15	.11	85	171	435
186	....		May 4 & 5	23.15	4.0	2.0	.21	.12	76	178	604
163	D2	Anthracite	February 24	8.00	5.0	2.0	.12	.05	82	174	536
167	....		March 2	17.52	6.0	2.0	.08	.05	85	173	528
187	....		May 4 & 5	26.00	5.5	2.0	.12	.07	76	178	500
172	D1	Pocahontas	March 17	10.07	5.0	2 0	.17	.12	84	164	389
174	....		March 21	17.03	3.5	1.5	.16	.12	83	170	643
176	....		March 23 & 24	25.13	4.0	2.0	.18	.13	80	175	594
173	D2	Pocahontas	March 11	12.65	5.5	2.0	.12	.09	83	156	482
175	....		March 21	16.05	5 5	2.0	.13	.07	83	171	554
177	....		March 23 & 24	25.93	5.5	2.0	.13	.08	80	173	525
178	D1	Gas House Coke	April 11	8.43	5.5	2.0	.13	.08	69	166	560
199	....		May 21	9.57	4.0	2.0	.13	.11	92	177	528
180	....		April 7	15.83	4.0	2.0	.12	.10	80	175	568
213	...		June 18	17.15	5 0	2.0	.30	.09	94	170	410
201	....		May 22 & 23	23.70	3.5	2.0	.17	.14	80	172	536
182	....		April 17 & 18	26.23	3.5	2.0	.10	.09	79	175	605
179	D2	Gas House Coke	April 6	11.70	6.0	2.0	.12	.07	83	174	499
200	....		May 21	11.85	5.5	2.0	.09	.05	91	175	479
181	....		April 7	14.92	6.0	2.0	.12	.07	80	173	497
185	....		May 2	15.55	5.5	2.0	.10	.06	72	146	472
183	....		April 17 & 18	24.85	6.0	2.0	.11	.07	80	173	421
202	....		May 22 & 23	24.17	6.0	2.0	.10	.06	80	175	481
197	D1	Solvay Coke	May 19	10.63	4.0	2.0	.14	.11	88	178	511
195	...		May 18	15.17	4.0	2.0	.13	.11	86	178	513
192			May 11 & 12	26.53	3.5	2.0	.15	.12	82	179	504

207	D_2	Solvay Coke	June 5	12.58	5.5	2.0	.06	.04	87	177	451
196	....		May 18	16.32	6.0	2.0	.09	.06	86	177	429
193	....		May 11 & 12	25.55	5.5	2.0	.08	.06	82	182	409
215	D_1	Illinois, Williamson county	June 22	8.63	4.5	2.0	.33	.04	102	182	412
211	....		June 16	17.68	5.0	2.0	.29	.06	83	166	436
217	....		June 25 & 26	23.48	5.0	2.0	.45	.02	84	173	617
214	D_2	Illinois, Williamson county	June 18	9.88	5.5	2.0	.07	.03	95	182	521
212	....		June 16	15.58	5.5	2.0	.09	.05	84	172	471
218	....		June 25 & 26	23.18	5.5	2.0	.19	.07	84	175	587
236	D_1	Illinois, Macon county	July 27	9.78	5.0	2.0	.35	.05	97	176	523
234	....		July 24	16.73	5.0	2.0	.25	.07	94	177	545
232	....		July 22 & 23	24.58	5.0	2.0	.38	.07	91	179	483
237	D_2	Illinois, Macon county	July 27	8.38	5.5	2.0	.13	.05	98	179	574
235	....		July 24	16.03	5.0	2.0	.16	.06	94	183	556
233	....		July 22 & 23	23.13	5.5	2.0	.13	.04	92	183	550
241	D_1	Illinois, Vermilion county	July 31	7.97	4.5	2.0	.38	.03	97	169	544
243	....		August 3	16.45	5.0	2.0	.40	.06	97	170	535
239	....		July 29 & 30	24.47	4.5	2.0	.32	.05	94	175	560
242	D_2	Illinois, Vermilion county	July 31	8.55	6.0	2.0	.18	.06	97	177	615
244	....		August 3	15.07	5.5	2.0	.17	.05	98	183	613
240	....		July 29 & 30	25.02	5.5	2.0	.16	.06	93	179	583

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[1] See "7. Tabulated Data and Results," p. 20.

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(*Continued*)

Test Number	Boiler	Kind of Fuel	Fuel as Fired (pounds)				Dry Fuel (pounds)			Total Ash and Refuse From Ash Pit (pounds)	Residual Fuel Removed (pounds)
			Wood	Coal	Coal Plus Wood	Corrected For Residual Fuel	Total Fired	Corrected For Residual Fuel	Actually Consumed (Corrected For Carbon in Ash)		
			20	**21**	**21.1**	**21.2**	**23**	**23.1**	**23.2**	**24**	**25**
162	D1	Anthracite	25	275	285	221	274	213	207	11.25	78.50
166	....		25	450	460	391	443	376	365	24.75	90.50
186	...		25	600	610	533	585	511	495	40.25	102.75
163	D2	Anthracite	30	315	327	225	314	216	206	14.75	115.25
167	...		30	525	537	452	517	435	414	39.00	105.50
187	....		30	735	747	637	716	610	587	47.00	146.50
172	D1	Pocahontas	15	225	231	217	226	213	204	14.00	21.00
174	...		15	375	381	369	373	361	352	17.75	24.00
176	....		15	600	606	595	594	584	564	36.25	29.00
173	D2	Pocahontas	20	315	323	303	317	297	277	28.25	32.00
175	....		20	420	428	406	419	398	378	31.50	33.00
177	....		20	630	638	621	625	608	581	44.50	26.75
178	D1	Gas House Coke	20	225	233	217	219	204	201	6.50	28.25
199	....		20	225	233	216	216	201	197	11.50	27.00
180	....		20	375	383	366	365	349	347	10.00	37.50
213	....		20	375	383	364	365	347	344	14.50	35.75
201	....		20	525	533	516	501	485	479	31.00	36.25
182	...		20	600	608	580	567	541	538	26.50	42.75
179	D2	Gas House Coke	25	315	325	298	301	275	270	11.75	40.50
200	...		25	315	325	297	301	275	268	17.75	40.00
181	....		25	420	430	396	410	378	373	15.50	52.00
185	...		25	420	430	401	414	386	382	10.90	53.00
183	....		25	630	640	603	597	563	559	28.00	53.00
202	...		25	630	640	613	602	577	569	38.25	49.50
197	D1	Solvay Coke	20	225	233	216	228	212	208	9.75	26.50
195	...		20	300	308	291	302	285	284	10.00	32.00
192	...		20	525	533	515	526	508	506	21.50	41.50

207	D2	Solvay Coke	25	315	325	302	321	298	293	14.50	37.25
196	....		25	420	430	404	422	396	388	26.00	42.50
193	....		25	630	640	610	631	601	590	29.50	58.25
215	D1	Illinois, Williamson county	20	225	233	224	215	207	203	14.75	14.50
211	....		20	450	458	446	430	418	416	20.25	31.00
217	....		20	600	608	594	567	554	549	41.25	29.25
214	D2	Illinois, Williamson county	25	315	325	307	305	288	281	21.75	24.00
212	....		25	525	535	516	502	484	476	40.00	27.50
218	....		25	735	745	729	695	680	673	55.50	32.50
236	D1	Illinois, Macon county	20	300	308	297	276	266	259	24.75	21.00
234	....		20	525	533	511	481	461	456	35.00	44.75
232	....		20	750	758	737	678	659	650	57.25	50.75
237	D2	Illinois, Macon county	25	315	325	309	291	277	267	26.75	27.50
235	....		25	630	640	616	578	556	545	44.25	51.75
233	....		25	840	850	834	760	746	736	67.25	47.00
241	D1	Illinois, Vermilion county	20	225	233	226	206	199	194	17.00	14.00
243	....		20	450	458	446	409	398	392	27.50	24.75
239	....		20	675	683	669	605	593	588	37.00	35.75
242	D2	Illinois, Vermilion county	25	315	325	311	287	275	266	29.00	19.50
244	....		25	525	535	522	478	467	457	36.50	26.75
240	....		25	840	850	823	753	729	717	56.25	40.50

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(*Continued*)

Test Numb	Boiler	Kind of Fue	Proximate Analysis (per cent)								
			Fuel as Fired					Dry Fuel			
			Fixed Carbon	Volatile	Moisture	Ash	Sulphur	Fixed Carbon	Volatile	Ash	Sulphur
			26	**27**	**28**	**29**	**34**	**26**	**27**	**29**	**34**
162	D_1	Anthracite	77.30	7.04	3.94	11.72	1.55	80.47	7.33	12.20	1.61
166	....		77.54	7.06	3.64	11.76	1.56	80.47	7.33	12.20	1.62
186	....		79.85	4.27	4.13	11.75	0.70	83.29	4.45	12.26	0.73
163	D_2	Anthracite	77.30	7.04	3.94	11.72	1.55	80.47	7.33	12.20	1.61
167	....		77.54	7.06	3.64	11.76	1.56	80.47	7.33	12.20	1.62
187	....		79.85	4.27	4.13	11.75	0.70	83.29	4.45	12.26	0.73
172	D_1	Pocahontas	73.36	19.50	1.97	5.17	0.98	74.83	19.89	5.28	1.00
174	....		73.32	19.49	2.02	5.17	0.98	74.83	19.89	5.28	1.00
176	....		73.32	19.49	2.02	5.17	0.98	74.83	19.89	5.28	1.00
173	D_2	Pocahontas	73.36	19.50	1.97	5.17	0.98	74.83	19.89	5.28	1.00
175	....		73.32	19.49	2.02	5.17	0.98	74.83	19.89	5.28	1.00
177	....		73.32	19.49	2.02	5.17	0.98	74.83	19.89	5.28	1.00
178	D_1	Gas House Coke	81.35	2.78	6.12	9.75	1.31	86.65	2.96	10.39	1.40
199	....		78.57	3.37	7.35	10.71	1.07	84.80	3.64	11.56	1.15
180	....		82.61	2.82	4.67	9.90	1.33	86.66	2.96	10.38	1.39
213	....		82.20	4.26	4.65	8.89	0.99	86.21	4.47	9.32	1.04
201	....		78.08	4.91	5.97	11.04	0.99	83.04	5.22	11.74	1.05
182	....		80.79	2.76	6.76	9.69	1.30	86.65	2.96	10.39	1.39
179	D_2	Gas House Coke	80.28	2.74	7.36	9.62	1.30	86.66	2.96	10.38	1.40
200	....		78.57	3.37	7.35	10.71	1.07	84.80	3.64	11.56	1.15
181	....		82.61	2.82	4.67	9.90	1.33	86.66	2.96	10.38	1.39
185	....		85.20	1.73	3.71	9.36	0.92	88.48	1.80	9.72	0.96
183	....		80.79	2.76	6.76	9.69	1.30	86.65	2.96	10.39	1.39
202	....		78.08	4.91	5.97	11.04	0.99	83.04	5.22	11.74	1.05
197	D_1	Solvay Coke	86.42	1.50	2.04	10.04	0.63	88.22	1.53	10.25	0.64
195	....		86.22	2.04	1.93	9.81	0.64	87.92	2.08	10.00	0.65
192	....		85.48	2.19	1.38	10.95	0.65	86.68	2.22	11.10	0.66

207	D2	Solvay Coke	85.63	2.70	1.31	10.36	0.66	86.76	2.74	10.50	0.67
196	....		86.22	2.04	1.93	9.81	0.64	87.92	2.08	10.00	0.65
193	....		85.48	2.19	1.38	10.95	0.65	86.68	2.22	11.10	0.66
215	D1	Illinois, Williamson county	49.60	34.20	7.83	8.37	1.92	53.81	37.11	9.08	2.08
211	...		46.86	38.48	6.21	8.45	2.23	49.96	41.03	9.01	2.38
217	....		48.95	34 68	6.69	9.68	2.04	52.46	37.17	10.37	2.19
214	D2	Illinois, Williamson county	47.03	37.60	6.10	9.27	1.99	50.09	40.04	9.87	2.12
212	....		46.86	38.48	6.21	8.45	2.23	49.96	41.03	9.01	2.38
218	. ..		48.95	34.68	6.69	9.68	2.04	52.46	37.17	10.37	2.19
236	D1	Illinois, Macon county	39.04	38.21	10.45	12.30	2.95	43.60	42.67	13.73	3.29
234	....		39.95	38.25	9.74	12.06	3.20	44.26	42.38	13.36	3.55
232	....		41.34	36.84	10.53	11.29	3.29	46.20	41.18	12.62	3.68
237	D2	Illinois, Macon county	39.04	38.21	10.45	12.30	2.95	43.60	42.67	13.73	3.29
235	...		39.95	38.25	9.74	12.06	3.20	44.26	42.38	13.36	3.55
233	....		41.34	36.84	10.53	11.29	3.29	46.20	41.18	12.62	3 68
241	D1	Illinois, Vermilion county	40.27	38.65	11.54	9.54	2.25	45.52	43.69	10.79	2.54
243	....		40.91	40.85	10.63	7.61	1.61	45.78	45.71	8.51	1.80
239	....		40.03	39.01	11.40	9.56	2.57	45.18	44.03	10.79	2.90
242	D2	Illinois, Vermilion county	40.27	38.65	11.54	9.54	2.25	45.52	43.69	10.79	2.54
244	....		40.91	40.85	10.63	7.61	1.61	45.78	45.71	8.51	1.80
240	....		40.03	39.01	11.40	9.56	2.57	45.18	44.03	10.79	2.90

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(*Continued*)

Test Number	Boiler	Kind of Fuel	Residual Fuel (per cent)		Ash (per cent)		Dry Fuel per Hour		B. t. u. per Pound Fuel	
			Carbon	Earthy Matter	Carbon	Earthy Matter	Pounds	Per Sq. Ft. of Grate Surface	Dry	As Fired
			37	**38**	**40**	**41**	**43**	**44**	**45**	**46**
162	D_1	Anthracite	70.50	29.50	46.07	53.93	24.29	5.68	13219	12698
166	....		66.82	33.18	38.45	61.55	22.72	5.31	13218	12737
186	....		65.01	34.99	36.76	63.24	22.07	5.16	13179	12635
163	D_2	Anthracite	76.65	23.35	62.98	37.02	27.00	4.50	13219	12698
167	....		70.18	29.82	49.26	50.74	24.83	4.14	13218	12737
187	....		65.13	34.87	44.78	55.22	23.16	3.91	13179	12635
172	D_1	Pocahontas	65.71	34.29	67.91	32.09	21.15	4.91	15055	14758
174	....		50.36	49.64	50.10	49.90	21.20	4.95	15055	14751
176	....		37.15	62.85	57.11	42.89	23.24	5.43	15055	14751
173	D_2	Pocahontas	63.06	36.94	70.31	29.69	23.48	3.91	15055	14758
175	....		66.18	33.82	66.53	33.47	21.80	4.13	15055	14751
177	....		63.69	36.31	62.78	37.22	23.45	3.91	15055	14751
178	D_1	Gas House Coke	46.71	53.29	34.66	65.34	24.20	5.65	12805	12021
199	....		49.05	50.95	28.76	71.24	21.00	4.91	12626	11698
180	....		38.11	61.89	18.89	81.11	22.05	5.15	12804	12206
213	....		44.06	55.94	15.53	84.47	20.23	4.73	12647	12659
201	....		38.41	61.59	18.05	81.95	20.46	4.78	12881	12112
182	....		54.06	45.94	9.61	90.39	20.63	4.82	12805	11939
179	D_2	Gas House Coke	57.30	42.70	35.55	64.45	23.50	3.92	12801	11862
200	....		56.52	43.48	36.49	63.51	23.21	3.87	12626	11698
181	....		54.55	45.45	29.45	70.55	25.34	4.22	12804	12206
185	....		47.17	52.83	38.66	61.34	24.82	4.14	13028	12545
183	....		56.47	43.53	12.93	87.07	22.66	3.78	12805	11939
202	....		44.71	55.29	19.45	80.55	23.87	3.98	12881	12112
197	D_1	Solvay Coke	53.57	46.43	31.98	68.02	19.91	4.66	12636	12378
195	....		45.65	54.35	10.10	89.90	18.79	4.39	12622	12378
192	....		37.37	62.63	8.65	91.35	19.15	4.47	12745	12569

207	D2	Solvay Coke	53.13	46.87	27.37	72.63	23.69	3.95	12823	12655
196	....		52.04	47.96	26.96	73.04	24 26	4.04	12622	12378
193	....		44.29	55.71	31.98	68.02	23.52	3 92	12745	12569
215	D1	Illinois, Williamson county	50.99	49.01	23.84	76.16	23.99	5.61	13227	12191
211	....		34.06	65.94	9.69	90.31	23.64	5.52	13207	12387
217	....		40.74	59.26	11.35	88.65	23.59	5.51	13079	12204
214	D2	Illinois, Williamson county	62.88	37.12	30.85	69.15	29.15	4.86	13092	12293
212	....		58.02	41.98	18.44	81.56	31.07	5.18	13207	12387
218	....		40.02	59.98	11.90	88.10	29.34	4.89	13079	12204
236	D1	Illinois, Macon county	39.51	60.49	25.02	74.98	27.20	6.36	12312	11025
234	....		37.88	62.12	12.69	87.31	27.56	6.44	12206	11017
232	....		31.18	68.82	12.60	87.40	26 81	6.26	12282	10989
237	D2	Illinois, Macon county	42.83	57.17	30.07	69.93	33.05	5.51	12312	11025
235	....		34.76	65.24	20.21	79.79	34.68	5.78	12206	11017
233	....		25.01	74.99	13.07	86.93	32.25	5.38	12282	10989
241	D1	Illinois, Vermilion county	41.04	58.96	27.61	72.39	24.97	5.83	12878	11392
243	....		40.04	59.96	15.93	84.07	24.19	5.65	13251	11842
239	..		30.07	69.93	11.96	88.04	24.23	5.66	12879	11411
242	D2	Illinois, Vermilion county	54.06	45.94	26.76	73 24	32.16	5.36	12878	11392
244	....		38.15	61.85	24.49	75.51	30.99	5 17	13251	11842
240	....		51.26	48.74	18.89	81.11	29.14	4.86	12879	11411

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(*Continued*)

Test Number	Boiler	Kind of Fuel	Moisture in Steam (per cent)	Factor for Correcting Quality of Steam	Water (pounds)			Factor of Evaporation	Water Per Hour (pounds)	
					Fed to Boiler	Corrected for Quality of Steam	Equivalent from and at 212°F.		Equivalent from and at 212°F.	From and at 212°F. Per sq. ft. of Water-heating Surface
			47	48	49	50	52	51	53	54
162	D1	Anthracite	0.96	.9912	1349	1337	1397	1.0450	159	3.64
166	....		0.93	.9914	2518	2496	2608	1.0450	158	3.62
186	.		1.10	.9898	3568	3532	3665	1.0376	158	3.62
163	D2	Anthracite	0.68	.9937	1577	1567	1633	1.0419	201	2.69
167	....		0.61	.9914	3432	3413	3559	1.0428	203	2.68
187	....		0.88	.9918	4960	4919	5104	1,0376	196	2.58
172	D1	Pocahontas	1.00	.9909	1423	1410	1484	1.0522	147	3.36
174	....		1.07	.9902	2460	2436	2547	1.0456	150	3.43
176	....		1.03	,9905	3963	3925	4085	1.0407	163	3.73
173	D2	Pocahontas	0.69	.9937	2372	2357	2500	1.0606	198	2.61
175	....		0.95	.9913	3286	3257	3404	1.0450	212	2.79
177	....		0 77	.9929	5261	5224	5448	1.0428	210	2.77
178	D1	Gas House Coke	1 05	9904	1387	1374	1443	1.0501	171	3.91
199	....		0.99	.9908	1404	1391	1445	1.0387	151	3.46
180	....		1.04	.9904	2393	2370	2466	1.0407	156	3.57
213	...		1.06	.9902	2513	2488	2602	1.0460	152	3 48
201	....		1,18	.9891	3538	3499	3653	1.0439	154	3.52
182	....		1.08	.9900	4047	4007	4170	1.0407	159	3.64
179	D2	Gas House Coke	0.84	.9922	2287	2269	2364	1.0419	202	2.66
200	....		0.80	.9926	2307	2290	2383	1.0407	201	2.65
181	....		0.78	.9928	2954	2933	3059	1,0428	205	2.70
185	....		0.82	.9926	3012	2990	3202	1.0710	206	2.72
183	....		0 75	.9931	4731	4698	4899	1,0428	197	2.60
202	....		0.93	.9914	4631	4594	4781	1.0407	198	2.61
197	D1	Solvay Coke	1.01	.9906	1629	1614	1675	1.0376	158	3.62
195	...		1.05	.9903	2270	2248	2333	1.0376	154	3.52
192	....		1 12	.9896	3910	3899	4042	1.0366	152	3.48

207	D2	Solvay Coke	0.87	.9919	2431	2411	2504	1.0387	199	2.62
196	....		0.85	.9921	3179	3154	3276	1.0387	201	2.65
193	....		0.86	.9920	4681	4644	4799	1.0334	188	2.48
215	D1	Illinois, Williamson county	0.98	.9909	1282	1270	1312	1.0334	152	3.48
211	...		1.09	.9900	2594	2568	2697	1.0501	153	3.50
217	....		1.09	.9899	3559	3523	3674	1.0428	156	3.57
214	D2	Illinois, Williamson county	1.01	.9906	1982	1963	2029	1.0334	205	2.70
212	....		1.01	.9907	3160	3131	3268	1.0439	210	2.77
218	....		1.03	.9905	4761	4716	4908	1.0407	212	2.79
236	D1	Illinois, Macon county	0.95	.9912	1494	1481	1540	1.0397	157	3.59
234	....		0.93	.9914	2598	2576	2676	1.0387	160	3.66
232	....		0.95	.9912	3719	3686	3821	1.0366	155	3.55
237	D2	Illinois, Macon county	0.61	.9943	1778	1768	1833	1.0366	219	2.89
235	....		0.79	.9926	3294	3270	3376	1.0324	211	2.78
233	..		0.77	.9928	4643	4610	4759	1.0324	206	2.72
241	D1	Illinois, Vermilion county	0.98	.9910	1205	1194	1250	1.0471	157	3.59
243	....		1.00	.9908	2488	2465	2578	1.0460	157	3.59
239	....		0.97	.9910	3718	3685	3835	1.0407	157	3.59
242	D2	Illinois, Vermilion county	0.70	.9935	1801	1789	1858	1.0387	217	2.86
244	....		0.68	.9937	3144	3124	3225	1.0324	214	2.82
240	....		0.75	.9930	4893	4859	5037	1.0366	201	2.65

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS MADE AT ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(*Continued*)

Test Number	Boiler	Kind of Fuel	Mean Load Carried		Percentage of Rated Capacity Developed (per cent)	Economic Results (pounds)			
						Equivalent Evaporation from and at 212° F. per pound		Fuel per Hour per 100 Sq. Ft. Radiating Surface	
			Sq. Ft. of Radiating Surface	Sq. Ft. of Radiating Surface plus Radiating Surface of Boiler		Fuel as Fired	Dry Fuel Consumed	As Fired	Dry
			55	**55.1**	**56**	**57**	**58**	**59**	**60**
162	D1	Anthracite	530	568	66.25	6.32	6.75	4.75	4.58
166	...		527	565	65.88	6.67	7.15	4.48	4.31
186	....		527	565	65.88	6.68	7.40	4.37	4.19
163	D2	Anthracite	680	783	63.26	7.26	7.93	4.14	3.97
167	....		677	780	62.98	7.87	8.60	3.81	3.67
187	....		653	756	60.74	8.01	8.70	3.75	3.59
172	D1	Pocahontas	496	528	61.25	6.84	7.27	4.40	4.32
174	....		500	538	62.50	6.90	7.24	4.33	4.24
176	....		543	581	67.88	6.87	7.24	4.36	4.28
173	D2	Pocahontas	660	763	61.40	8.25	9.03	3.63	3.56
175	....		707	810	65.77	8.38	9.01	3.58	3.51
177	....		700	803	65.11	8.77	9.38	3.42	3.35
178	D1	Gas House Coke	570	608	71.25	6.65	7.18	4.52	4.25
199	....		503	541	62.88	6.69	7.34	4.49	4.17
180	....		520	558	65.00	6.74	7.11	4.45	4.24
213	....		507	515	63.38	7.15	7.56	4.19	3.99
201	...		513	551	64.13	7.08	7.63	4.24	3.99
182	...		530	568	66.25	7.19	7.75	4.17	3.89
179	D2	Gas House Coke	673	776	62.60	7.99	8.76	3.76	3.49
200	....		670	773	62.33	8.02	8.89	3.74	3.46
181	....		683	786	63.53	7.72	8.20	3.89	3.71
185	....		687	790	63.91	7.99	8.38	3.75	3.61
183	....		657	760	61.12	8.12	8.76	3.69	3.45
202	...		660	763	61.40	7.80	8.40	3.84	3.62
197	D1	Solvay Coke	527	565	65.88	7.75	8.05	3.86	3.78
195	....		513	551	64.13	8.02	8.21	3.71	3.63
192	....		507	545	63.38	7.85	7.99	3.83	3.78

207	D2	Solvay Coke	663	766	61.67	8.29	8.55	3.62	3.57
196	....		670	773	62.33	8.11	8.44	3.70	3.62
193	....		627	730	58.33	7.87	8.13	3.81	3.75
215	D1	Illinois, Williamson county	507	545	63.38	5.86	6.46	5.12	4.73
211	....		510	548	63.75	6.05	6.48	4.95	4.64
217	....		520	558	65.00	6.19	6.69	4.86	4.54
214	D2	Illinois, Williamson county	683	786	63.53	6.61	7.22	4.55	4.27
212	....		700	803	65.12	6.33	6.87	4.73	4.44
218	....		707	810	65.77	6.73	7.29	4.45	4.15
236	D1	Illinois, Macon county	523	561	65.40	5.19	5.95	5.81	5.20
234	....		533	571	66.63	5.24	5.87	5.73	5.17
232	....		517	555	64.60	5.18	5.88	5.80	5.19
237	D2	Illinois, Macon county	730	833	67.91	5.93	6.87	5.07	4.55
235	....		703	806	65.40	5.48	6.19	5.47	4.93
233	....		687	790	63.91	5.71	6.47	5.25	4.69
241	D1	Illinois, Vermilion county	523	561	65.40	5.53	6.44	5.42	4.77
243	....		520	558	65.00	5.78	6.56	5.21	4.65
239	....		520	558	65.00	5.73	6.52	5.26	4.66
242	D2	Illinois, Vermilion county	723	826	67.30	5.97	6.98	5.03	4.45
244	....		713	816	66.30	6.18	7.06	4.86	4.35
240	....		670	773	62.30	6.12	7.03	4.91	4.35

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS MADE AT ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(*Continued*)

Test Number	Boiler	Kind of Fuel	Efficiency (per cent)		Fuel $1.00 per 2000 lb.		Fuel Fired at Each Firing (pounds)	Average Interval (hours)		Maximum Interval of Maintaining 2 lb. or more Steam Pressure Without Attention
			Boiler and Furnace	Plant	Cost in Cents per 100 sq. ft of Radiating Surface per hour (Mean Load Carried on Test)	Cost of Evaporating 1000 lb. of Water from and at 212° F. (cents)		Between Firings	Between Times of Shaking and Raking	
			61	**62**	**64**	**65**	**70**	**71**	**72**	**73**
162	D_1	Anthracite	49.32	48.07	.238	7.91	75	2.19	2.19	3.17
166			52.24	50.58	.224	7.50	75	2.76	1.84	3.43
186			54.23	52.59	.219	7.27	75	2.47	2.19	3.00
163	D_2	Anthracite	57.94	55.22	.207	6.89	105	2.67	2.00	4.55
167			62.84	59.68	.191	6.35	105	3.50	1.95	3.67
187			63.76	61.23	.188	6.24	105	3.71	2.89	4.67
172	D_1	Pocahontas	46.64	44.76	.220	7.31	75	3.36	1.01	1.87
174			46.45	45.18	.217	7.24	75	3.41	0.71	2.00
176			46.45	44.98	.218	7.28	75	3.14	0.63	1.20
173	D_2	Pocahontas	57.93	53.99	.182	6.06	105	4.22	0.84	2.63
175			57.80	54.87	.179	5.97	105	4.01	1.00	3.60
177			60.17	57.42	.171	5.70	105	4.32	0.93	2.82
178	D_1	Gas House Coke	54.15	53.43	.226	7.52	75	2.81	2.81	1.70
199			56.15	55.23	.225	7.47	75	3.19	2.39	3.00
180			53.63	53.33	.223	7.42	75	3.17	3.17	3.00
213			57.73	57.26	.210	6.99	75	3.43	3.43	3.33
201			57.21	56.46	.212	7.06	75	3.39	2.63	3.33
182			58.45	58.16	.209	6.95	75	3.28	3.28	3.00
179	D_2	Gas House Coke	66.08	65.05	.188	6.26	105	3.90	2.34	3.00
200			68.00	66.21	.187	6.23	105	3.95	1.98	3.00
181			61.85	61.08	.195	6.48	105	3.73	2.13	3.33
185			62.12	61.51	.188	6.26	105	3.89	1.95	3.33
183			66.07	65.69	.185	6.16	105	4.14	4.14	4.10
202			62.98	62.20	.192	6.41	105	4.03	2.42	4.00
197	D_1	Solvay Coke	61.53	60.47	.193	6.45	75	3.54	3.54	3.66
195			62.82	62.58	.186	6.23	75	3.79	3.79	3.86
192			60.55	60.32	.192	6.37	75	3.79	3.79	3.66

207	D2	Solvay Coke	64.40	63.27	.181	6.03	105	4.19	2.52	3.58
196	....		64.58	63.28	.185	6.17	105	4.08	3.26	4.00
193	....		61.61	60.47	.191	6.35	105	4.26	2.84	4.00
215	D1	Illinois, Williamson county	47.17	46.42	.256	8.53	75	2.88	1.08	1.33
211	....		47.39	47.17	.248	8.26	75	2.95	1.47	1.66
217	....		49.40	48.99	.243	8.08	75	2.93	0.84	1.33
214	D2	Illinois, Williamson county	53.26	51.93	.228	7.56	105	3.29	1.41	2.00
212	....		50.24	49 35	.237	7.90	105	3.12	1.42	2.00
218	....		53.83	53.26	.223	7.43	105	3.31	1.01	2.00
236	D1	Illinois, Macon county	46.67	45.46	.291	9.65	75	2.45	0.98	1.33
234	....		46.45	45.94	.287	9.56	75	2.39	1.05	1.66
232	....		46.24	45.53	.290	9.67	75	2.46	0.95	1.66
235	D2	Illinois, Macon county	53.89	51.95	.254	8.43	105	2.79	1.05	1.66
232	....		48.98	48.04	.275	9.12	105	2.67	1.14	1.33
233	....		50.88	50.18	.263	8.77	105	2.89	1.16	2.00
241	D1	Illinois, Vermilion county	48.30	46.88	.271	9.06	75	2.66	0.66	1.00
243	....		47.81	47.14	.261	8.67	75	2.74	0.97	1.33
239	....		48.89	48.50	.263	8.74	75	2.72	0.94	1.66
242	D2	Illinois, Vermilion county	52.35	50.61	.252	8.38	105	2.85	0.86	0.66
214	....		51.46	50.40	.243	8.09	105	3.01	1.16	1.66
240	....		52,72	51,80	.246	8.17	105	3.13	1.04	1.33

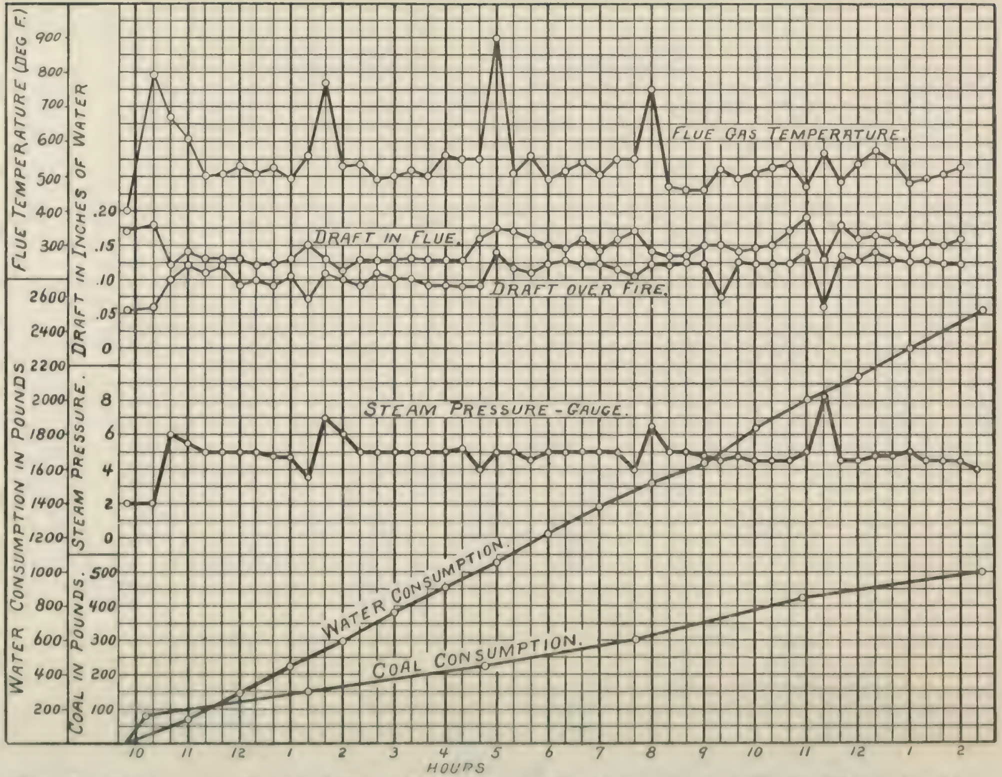

FIG. 18 GRAPHICAL LOG FOR TEST 166—BOILER D_1—ANTHRACITE COAL (House-heating boiler tests with representative fuels). (See "6. Test Data," p. 20).

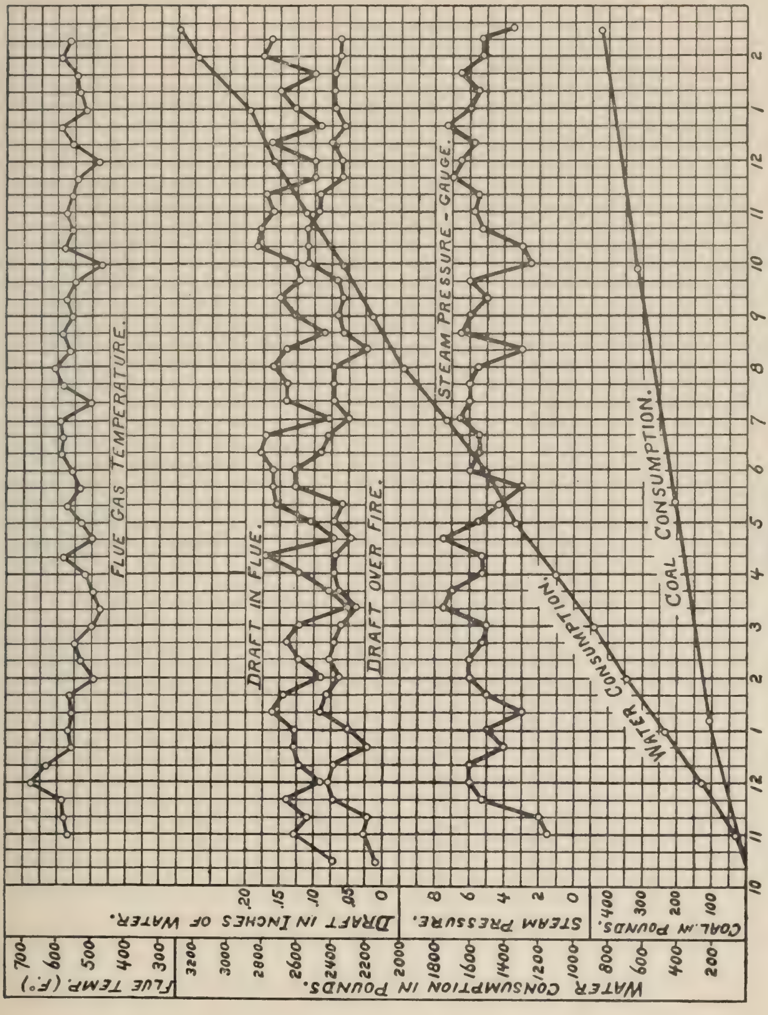

FIG. 19 GRAPHICAL LOG FOR TEST 175—BOILER D_2—POCAHONTAS COAL

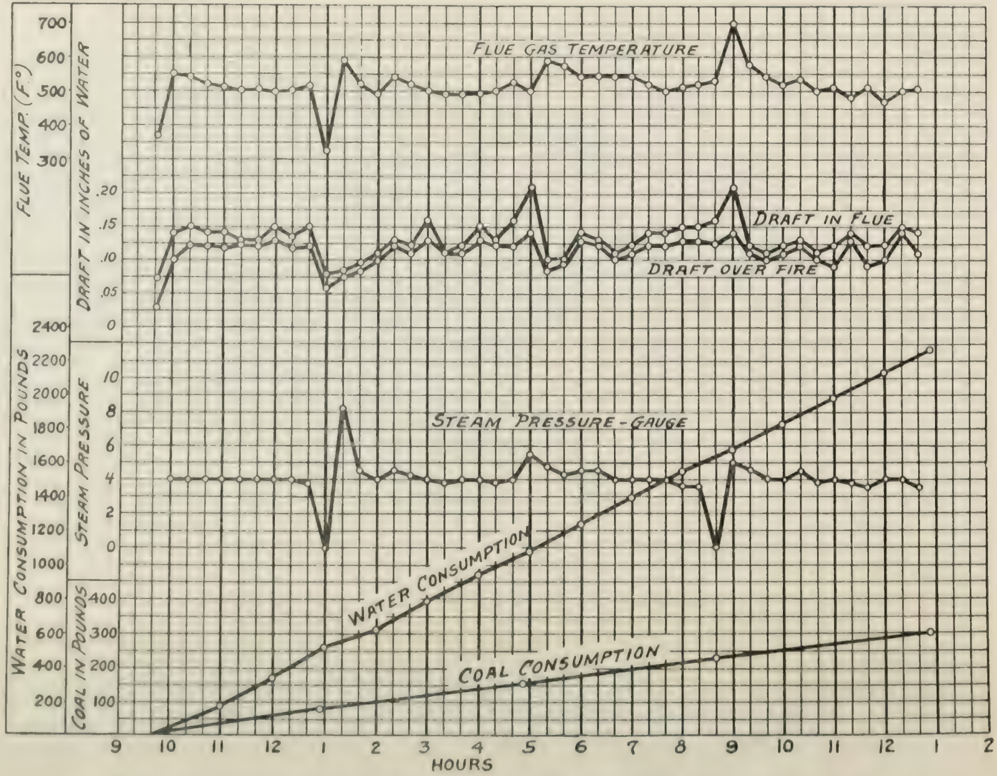

FIG. 20 GRAPHICAL LOG FOR TEST 195—BOILER D_1—SOLVAY COKE

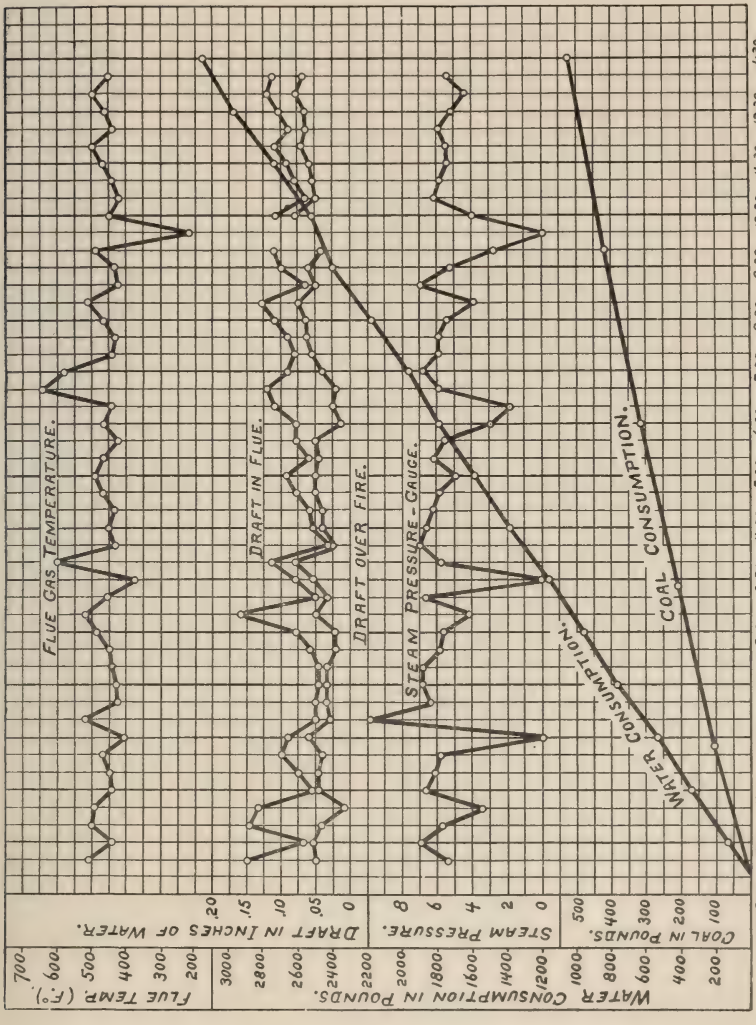

FIG. 21 GRAPHICAL LOG FOR TEST 212—BOILER D_2—ILLINOIS COAL (Williamson Co.)

TABLE 13

FLUE GAS ANALYSES, HOUSE-HEATING BOILER TRIALS WITH REPRESENTATIVE FUELS*

Kind of Fuel	Test No.	Length of Test (hours)	CO_2 per cent	O_2 per cent	Average	
					CO_2 per cent	O_2 per cent
BOILER D1						
Anthracite	162	8.76	3.6	14.6		
	186	23.15	6.4	11.4	5.0	13.0
Pocahontas	176	25.13	3.5	16.2	3.5	16.2
Gas House Coke	199	9.57	9.4	11.1		
	180	15.83	3.7	16.0		
	201	23.70	8.2	12.2		
	182	26.23	6.0	13.5	6.8	13.2
Solvay Coke	197	10.63	9.1	11.3		
	195	15.17	8.3	12.0	8.7	11.7
Illinois, Williamson county	215	8.63	6.7	12.8		
	217	23.48	6.8	12.8	6.8	12.8
Illinois, Macon county	234	16.73	6.2	13.4	6.2	13.4
BOILER D2						
Anthracite	163	8.00	8.8	10.7		
	167	17.52	9.9	9.7		
	187	26.00	8.9	9.6	9.2	10.0
Pocahontas	175	16.05	7.6	10.1		
	177	25.93	8.7	9.3	8.2	9.7
Gas House Coke	179	11.70	9.3	7.4		
	200	11.85	15.3	4.4		
	185	15.55	14.4	5.0		
	181	14.92	12.0	6.7		
	183	24.85	11.7	6.9		
	202	24.17	13.5	6.3	12.7	6.1
Solvay Coke	209	12.57	14.3	4.7		
	196	16.33	12.1	7.3	13.2	6.0
Illinois, Williamson county	214	9.88	10.4	6.7		
	212	15.58	11.7	4.5		
	218	23.18	5.1	14.8	9.1	8.7
Illinois, Macon county	235	16.03	11.4	5.9	11.4	5.9

*See "7. Tabulated Data and Results," p. 20.

TABLE 14

COMPARISON OF FLUE GAS ANALYSES TAKEN AT DIFFERENT TIMES DURING TEST, BOILER D_2, HOUSE-HEATING BOILER TRIALS WITH REPRESENTATIVE FUELS

Fuel	Time of Starting Sample	Length of Time of Collecting Sample (min.)	When Taken	CO_2 per cent	O_2 per cent
Anthracite	10:00 A. M.	20	Just after 2nd firing.............	7.2	9.6
	11:00 A. M.	35	1 hour after 2nd firing............	9.0	10.0
	12:00 M.	45	2 hours after 2nd firing...........	8.4	10.4
	2:05 P. M.	60	45 minutes after 3rd firing........	11.1	7.9
Gas House Coke	9:45 A. M.	60	37 minutes after 1st firing........	14.0	5.7
	12:25 P. M.	60	15 minutes after 2nd firing........	14.4	3.9
	2:10 P. M.	80	2 hours after 2nd firing...........	14.8	5.3
	4:20 P. M.	20	2 minutes after 3rd firing	11 3	7.3
	5:10 P. M.	30	52 minutes after 3rd firing........	16.5	3.6
	6:00 P. M.	60	1 hour 42 min. after 3rd firing....	15.6	4.4
Solvay Coke	9:15 A. M.	45	1 hour after 1st firing*.	15.1	4.1
	10:45 A. M.	30	2 hours 30 min. after 1st firing **	12.2	7.0
	10:00 A. M.	60	47 minutes after 1st firing........	13.8	5.6
	12:00 M.	60	2nd firing at 12:45................	10.8	9.2
	2:35 P. M.	60	1 hour 50 min. after 2nd firing ..	13.2	4.6
	4:30 P. M.	40	3 hours 45 min. after 2nd firing...	10.5	9.8
Illinois, Williamson county	9:25 A. M.	30	30 minutes after 1st firing†.......	7.9	9.8
	10:00 A. M.	30	65 minutes after 1st firing††......	9.7	8.1
	11:52 A. M.	30	Just after 2nd firing..............	8.0	8.7
	12:30 P. M.	30	40 minutes after 2nd firing	12.4	4.6
	2:30 P. M.	34	1 hour before 3rd firing...........	13.3	6.2
	3:35 P. M.	..	Just after 3rd firing.......... ...	11.4	2.8

* Fire hot and thick. ** Fire thin, with several holes.

Both of these samples on test No. 207. Other four coke samples on test No. 196.

† Fire badly caked. †† Fire clear and bright.

TABLE 15

SMOKE CHART RECORD, HOUSE-HEATING BOILER TRIALS WITH REPRESENTATIVE FUELS

Boiler No.	Kind of Fuel	Test No.	Number of Firing after which Smoke Record was Made	Color or Condition of Smoke	Maximum Density of Smoke Recorded		Percent of Firing Interval During Which Smoke Was Produced	Percent of Firing Interval During Which No Smoke Was Produced	Percent of Black Smoke for Test Based Upon the Intervals Observed
					per cent	No. on Ringelmann Chart	per cent	per cent	per cent
D1	Gas House Coke..........	199	3rd	....	40	2	7	93	2
D1	"	213	1st	Dense Yellow.....	50	2.5	9	91	3
D2	"	200	3rd	....	20	1	7	93	1
D2	"	185	3rd	....	40	2	6	94	2
D1	Solvay Coke.	195	1st	Gray Yellow......	50	2.5	7	93	2
D1	"	192	2d &6 th	Light Gray..	10	0.5	5	95	0
D2	"	196	1st	Light Yellow......	50	2.5	10	90	3
D2	"	193	1st	Light Gray..	60	3	15	85	3
D1	Williamson county, Illinois.............	211	3rd	....	40	2	50	50	14
D1	"	217	2nd	Yellow,black,gray	70	3.5	49	51	11
D2	"	214	1st	....	60	3	48	52	13
D1	Macon county, Illinois...	236	2nd	....	70	3.5	48	52	16
D1	"	234	2nd	....	40	2	40	60	13
D1	"	232	2nd	....	50	2.5	64	36	24
D2	"	237	2nd	....	60	3	61	39	22
D2	"	235	2nd	....	60	3	44	56	17
D2	"	233	2nd	....	60	3	27	73	10
D1	Vermilion county, Illinois....	241	3rd	....	60	3	44	56	18
D1	"	243	4th	....	50	2.5	34	66	13
D1	"	239	2nd	....	60	3	56	44	24
D2	"	242	3rd	....	70	3.5	60	40	23
D2	"	244	4th	....	60	3	50	50	15
D2	"	240	2nd	... .	50	2.5	45	55	16

APPENDIX B

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT ST. LOUIS*

Test No.	Designation of Fuel	Description of Fuel	Duration of Trial hours	Average Pressures				
				Steam Pressure in Boiler (gage)	Barometer (lb. per sq. in.)	Draft in. of water		
						Between Damper and Boiler	Over Fire	In Ashpit
			1	10	11.1	12	13	13.1
45	Arkansas No. 13	Briquets, round	8.33	2.2	14.39	0.34	0.07	0.04
58	Illinois No 1	Coal, run-of-mine	7.92	1.9	14.36	.33	.07	.03
59	"	"	8.00	1.9	14.45	.36	.05	.03
48	Illinois No. 7 .E	Briquets, round	8 00	1.7	14.45	.33	.06	.03
39	Illinois No. 9 C	"	8.30	1.7	14.54	.36	.07	.04
13	Illinois No 12 BW	Briquet, square, slack	8.25	3.8	14.39	.21	.06	.05
52	Illinois No. 19 E	Coal, egg	7.80	2.4	14.56	.31	.03	.03
53	"	"	8.25	2.3	14.41	.35	.05	.04
54	"	"	8.06	2.1	14.30	.32	.03	.02
55	"	"	7.83	1.3	14.35	.36	.03	.02
9	Illinois No. 29 AW	Briquets, round	7.88	3.4	14.46	.24	.10	.06
12	Illinois No. 29 B	Briquets, round, slack	7.20	2.2	14.51	.23	.08	.07
33	Illinois No. 31.	Briquets, square	7.83	2.7	14.37	.29	.13	.10
34	"	"	8.08	2.9	14.34	.28	.10	.06
44	"	Briquets, round	8.33	1.8	14.40	.36	.07	.04
43	Illinois No. 33	"	7.83	2.2	14.34	.32	.08	.05
37	Indiana No. 1 B	"	8.33	2.4	14.60	.35	.13	.07
36	Indiana No. 5 B	"	8.41	2.7	14.26	.34	.13	.08
38	Indiana No. 6 B	Briquets, square	7.88	2.8	14.64	.35	.09	.06
10	Indian Territory No. 2 BW	Briquets, square, slack	7.92	3.3	14.59	.25	.12	....
11	Indian Territory No. 2 B.	Briquets, round, slack	7.87	4.3	14.51	.22	.05	.04
1	Kansas No. 2 B	"	8.00	4.1	14.46	.22	.05	.03
40	"	Briquets, square	8.25	2.5	14.36	.36	.09	.06
21	Maryland No. 2.	Briquets, round	8.00	2.9	14.65	.28	.12	.09
22	"	"	7.50	3.2	14.55	.23	.11	.10
23	"	"	8.00	3.6	14.51	.23	.11	.10
20	"	Coal, run-of-mine	7.88	2.2	14.52	.25	.13	.09
2	Missouri No. 10	Briquets, round, slack	7.66	3.4	14.68	.24	.04	.03
3	"	"	7.83	3.1	14.46	.21	.07	.05
4	"	"	7.82	3.2	14.54	.25	.08	.06
5	"	"	8.13	2.0	14.59	.26	.10	.05
28	Pennsylvania No. 18	Briquets, round	8.00	3.9	14.37	.18	.09	.08
29	"	"	8.00	4.6	14.44	.18	.07	.06
30	"	Briquets, square	7.70	3.3	14.51	.22	.11	.10
31	"	"	8.00	3.4	14.60	.29	.12	.10
46	"	"	8.13	2.1	14.40	.36	.03	.01
24	"	Coal, run-of-mine	8.00	3.0	14.55	.22	.10	.09
25	"	"	8.00	3.1	14.41	.22	.13	....
32	Pennsylvania No. 19	Briquets, round	6.58	3.6	14.33	.27	.11	.07
15	"	Coal, run-of-mine	7.50	3.4	14.43	.23	.11	.10
26	Pennsylvania No. 20	Briquets, square	8.00	3.4	14.48	.23	.12	....
27	"	"	8.00	3 3	14.40	.22	.11	....
41	Pennsylvania No. 20 W	Briquets, round	7.81	3.3	14.30	.32	.07	.06
42	"	"	5.20	2.9	14 32	.33	.09	.08
16	Pennsylvania No. 22	"	7.83	3.7	14.46	.22	.11	.08
17	"	"	8.08	3.5	14.28	.21	.09	.08
18	"	Briquets, square	8.00	1.6	14.36	.23	.09	.07
19	"	"	8.05	2.4	14.36	.23	.12	.11
14	"	Coal, run-of-mine	7.58	3.8	14.55	.23	.10	.07
47	Pennsylvania No. 15 (one half) and Rhode Island No. 1 (one-half).	Briquets, round	8.23	2.0	14.51	34	.07	.03
56	Pennsylvania No 18 (one-fourth) and Miscellaneous No.9 (three-fourths)	"	8.16	1.6	14.38	.34	.04	.02
57	"	"	7.00	2 2	14.47	.36	.07	04
35	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half).	"	5.66	3.2	14.31	.29	.10	.07
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth).	"	8.23	3.0	14.45	.30	.06	.04
50	Pennsylvania No 18 (one-half) and Miscellaneous No. 9 (one-half).	"	7.83	2.2	14.40	.34	.07	.04
51	"	"	8.00	2.5	14.46	.33	.04	.02
7	Virginia No. 5 B	"	8.00	3.6	14.46	.24	.12	.10
8	"	"	7.80	4.8	14.35	.19	.09	.07

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*See '15. Data and Results," p. 58.

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT ST. LOUIS—(*Continued*)

Test No.	Designation of Fuel	Average Temperature (°F)				Fuel as Fired pounds	Dry Fuel pounds	Total Dry Fuel Fired minus Dry Fuel Equivalent to the Carbon in the Ash pounds	Total Ash and Refuse from Ashpit (pounds)
		External Air	Boiler Room	Feed Water in Weigh Tank	Gases Escaping from Boiler				
		14	15	16	17	21	23	23.2	24
45	Arkansas No. 13	50	81	145	695	777	765	731	137
58	Illinois No. 1	64	88	121	710	854	739	706	151
59	''	46	73	126	720	874	756	728	128
48	Illinois No. 7 E	45	77	141	650	965	907	874	237
39	Illinois No. 9 C	58	83	137	855	871	824	789	195
13	Illinois No. 12 BW	69	92	143	...	666	613	587	98
52	Illinois No. 19 E	59	88	138	600	817	757	727	114
53	''	66	88	128	720	927	859	827	122
54	''	62	85	135	635	811	752	725	104
55	''	72	93	123	850	764	708	685	87
9	Illinois No. 29 AW	31	70	149	...	750	658	648	68
12	Illinois No. 29 B	46	79	147	...	735	688	671	106
33	Illinois No. 31	80	91	106	570	813	738	725	112
34	''	82	96	101	400	836	759	743	139
44	''	51	82	138	795	968	901	880	144
43	Illinois No. 33	50	81	146	600	974	882	761	333
37	Indiana No. 1 B	57	91	120	815	1104	1056	1037	120
36	Indiana No. 5 B	63	90	103	730	929	890	868	134
38	Indiana No. 6 B	45	82	140	715	815	768	750	144
10	Indian Territory No. 2 BW	33	71	150	...	736	720	686	100
11	Indian Territory No. 2 B	42	76	158	...	737	721	700	126
1	Kansas No. 2 B	40	72	145	...	667	648	...	113
40	''	48	84	135	665	800	772	743	172
21	Maryland No. 2	31	74	150	...	652	628	612	73
22	''	30	80	146	...	560	540	534	28
23	''	41	73	143	...	650	626	611	67
20	''	32	71	144	...	520	511	502	34
2	Missouri No. 10	32	70	151	...	1159	1031	986	258
3	''	57	83	149	...	769	684	651	189
4	''	27	69	139	...	819	729	695	193
5	''	18	67	154	...	1036	922	898	136
28	Pennsylvania No. 18	46	81	140	...	580	537	531	37
29	''	54	85	144	...	662	604	598	34
30	''	42	83	146	...	525	500	496	31
31	''	58	81	146	550	550	524	516	68
46	''	44	80	133	685	653	636	610	110
24	''	43	78	144	...	550	539	527	47
25	''	42	74	145	...	550	530	518	47
32	Pennsylvania No. 19	86	96	112	675	541	532	527	41
15	''	55	85	142	...	456	447	438	27
26	Pennsylvania No. 20	44	77	145	...	525	493	484	55
27	''	52	85	141	...	550	516	508	48
41	Pennsylvania No. 20 W	48	84	146	570	594	587	577	56
42	''	45	76	134	620	388	383	374	53
16	Pennsylvania No. 22	48	78	141	...	550	538	520	117
17	''	63	..	138	...	538	526	515	72
18	''	47	79	140	...	553	533	503	92
19	''	46	77	140	...	551	531	504	84
14	''	47	81	144	...	492	483	459	97
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half)	45	77	147	665	652	647	616	112
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths)	50	80	126	800	644	637	606	112
57	''	53	83	125	730	652	645	613	117
35	Pennsylvania No. 18 (one-half) and Rhode Island No, 1 (one-half)	84	99	102	705	489	482	475	46
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth)	47	79	142	550	648	636	609	130
50	Pennsylvania No. 18 (one-half) and Miscellaneou2 No. 9 (one-half)	47	80	140	630	646	638	596	133
51	''	49	79	139	620	651	643	598	142
7	Virginia No. 5 B	37	72	157	...	712	680	639	154
8	''	45	77	155	...	613	585	549	134

TABLE 16 Tests of Fuel in House-heating Boiler at St. Louis—(*Continued*)

Test No.	Designation of Fuel	Proximate Analysis of Fuel as Fired per cent				Ultimate Analysis of Dry Fuel per cent					
		Fixed Carbon	Volatile Matter	Moisture	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash
		26	27	28	29	30	31	32	33	34	35
45	Arkansas No. 13	68.30	15.11	1.49	15.10	75 05	3.84	1.81	1.35	2.62	15.33
58	Illinois No. 1	41.39	33.15	13.49	11.97	64.88	4.45	10.71	1.03	5.09	13.84
59	"	41.39	33.15	13.49	11.97	64 88	4.45	10.71	1.03	5.09	13.84
48	Illinois No. 7 E	40.34	30.09	6.06	23.51	59.48	3.54	5.70	.83	5.42	25.03
39	Illinois No. 9 C	47.63	33.55	5.43	13.39	68.44	4.44	8.30	.94	3.72	14.16
13	Illinois No. 12 BW	49.47	31.55	7.93	11.05	71.14	4.39	8.90	1.12	2.45	12.00
52	Illinois No. 19 E	51.22	31.00	7.33	10.45	.....	....	.....	....	2.76	.....
53	"	51.22	31.00	7.33	10.45	.....	....	.....	....	2.76	.....
54	"	51.22	31.00	7.33	10.45	.....	....	.....	....	2.76	.....
55	"	51.22	31.00	7.33	10 45	.....	....	.....	....	2.76	.....
9	Illinois No. 29 AW	43.99	37 16	12.29	6.56	72.22	4.92	10.25	1.07	4.06	7.48
12	Illinois No. 29 B	44.21	37.44	6.42	11.93	67.10	4.59	10.30	1.00	4 26	12.75
33	Illinois No. 31	43.90	33.03	9.17	13.90	66.14	4.33	8.93	1.01	4.29	15.30
34	"	43.90	33.03	9.17	13.90	66.14	4.33	8.93	1.01	4.29	15.30
44	"	42.85	35.21	6.98	14.96	66.75	4.85	7.33	.93	4.06	16.08
43	Illinois No. 33	40.75	28.25	9.47	21.53	60.07	3.93	9.47	1.03	1.72	23.78
37	Indiana No 1 B	44.78	36.21	4.34	14.67	65.26	4.58	10.84	1.20	2.78	15.34
36	Indiana No. 5 B	48.91	35.74	4.20	11.15	70.47	4.85	7.53	.94	4.57	11.64
38	Indiana No. 6 B	43.16	37.83	5.72	13.29	66.48	4.76	8.42	1.07	5.17	14.10
10	Indian Territory No. 2 BW	54.51	35.86	2.19	7.44	75.69	4.84	8.76	1.53	1.57	7.61
11	Indian Territory No. 2 B	51.31	34.60	2.15	11.94	71.96	4.56	8.09	1.45	1.74	12.20
1	Kansas No. 2 B	46.78	31.67	2.78	18.77	66.00	4.35	4.90	.96	4.48	19.31
40	"	47.58	29.09	3.47	19.86	63.78	4.01	5.92	1.03	4.69	20.57
21	Maryland No. 2	68.54	21.14	3 63	6.69	82.41	4.74	3.40	1.62	.89	6 94
22	"	68 54	21.14	3.63	6.69	82 41	4.74	3.40	1.62	.89	6.94
23	"	68.54	21.14	3.63	6.69	82.41	4.74	3.40	1.62	.89	6.94
20	"	71.25	18.69	1.69	8.37	.....	....	....	....	.92	....
2	Missouri No 10	38.67	32.24	11.03	18 06	.....	....	....	....	4.18	....
3	"	38.67	32.24	11.03	18.06	.....	....	....	....	4.18	....
4	"	38.67	32.24	11.03	18.06	.....	....	....	....	4.18	....
5	"	38.67	32.24	11.03	18.06	....	....	....	....	4.18	...
28	Pennsylvania No. 18	64.61	19.45	7.43	8 51	80.80	4.44	2.88	1.16	1.53	9.19
29	"	64.61	19.45	7.43	8.51	80.80	4.44	2.88	1.16	1.53	9.19
30	"	69.14	18.43	4.71	7.72	81.77	4.40	3.22	1.26	1.25	8.10
31	"	69.14	18.43	4.71	7.72	81.77	4.40	3.22	1.26	1.25	8.10
46	"	62.80	24.23	2.55	10.42	78.65	4.36	3.38	.88	2.04	10.69
24	"	71.55	16.71	1.96	9.82	.....	....	...	...	1.91	.....
25	"	71.88	16.46	3.56	8.10	.....	....	....	....	1.76	.....
32	Pennsylvania No. 19	55 24	33.50	1.75	9.51	75.91	4.52	7.16	1.35	1.38	9.68
15	"	57.20	31.71	2.03	9.06	.....	....	....	....	1.15	.....
26	Pennsylvania No. 20	64.38	19.23	6.16	10.23	78.13	4.20	2.83	1.09	2.85	10.90
27	"	64 38	19.23	6.16	10.23	78.13	4.20	2.83	1.09	2.85	10.90
41	Pennsylvania No. 20 W	67.74	20.58	1.23	10.45	79.20	4.56	1.52	1.12	3.02	10.58
42	"	67.74	20 58	1.23	10.45	79.20	4.56	1.52	1.12	3 02	10.58
16	Pennsylvania No. 22	55.12	32.11	2.21	10.56	75.72	4.52	6.41	1.39	1.16	10.80
17	"	55.12	32.11	2.21	10.56	75.72	4.52	6.41	1.39	1.16	10.80
18	"	54.27	30.57	3.55	11.61	75.93	4.58	5.10	1.24	1.11	12.04
19	"	54.27	30.57	3.55	11.61	75.93	4.58	5.10	1.24	1.11	12.04
14	"	57.96	29.45	1.77	10.82	.....	....	....	....	.90	....
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half)	69.71	15.96	.74	13.59	77.47	3.05	2.66	.49	2.64	13.69
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths)	69.24	15.87	1.06	13.83	76.03	2.81	4.92	.81	1.45	13.98
57	"	69.24	15.87	1.06	13.83	76.03	2.81	4.92	.81	1.45	13.98
35	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half)	70.34	16.39	1.34	11.93	77.79	3.46	4.74	.53	1.39	12.09
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth)	69.52	15.05	1.83	13.60	77.21	3.12	3.48	.70	1.64	13.85
50	Pennsylvania No. 18 (one-half) and Miscellaneous No 9 (one-half)	69.67	13.73	1.30	15.30	70.93	2.81	8.80	.75	1.21	15.50
51	"	69.67	13.73	1.30	15.30	70.93	2.81	8.80	.75	1.21	15.50
7	Virginia No. 5 B	65.93	14.28	4.52	15.27	76.18	3.67	2.52	.81	.83	15.99
8	"	65.93	14.28	4.52	15.27	76.18	3.67	2.52	.81	.83	15.99

TABLE 16 TESTS OF FUEL IN HOUSE HEATING BOILER AT ST. LOUIS—(*Continued*)

Test No.	Designation of Fuel	Analysis of Ash and Refuse per cent		Fuel per hour pounds				British thermal units per pound of Fuel	
						Burned per square foot of Grate Surface			
		Carbon	Earthy Matter	As Fired	Dry	As Fired	Dry	Dry	As Fired
		37	**38**	**43**	**43.1**	**44.1**	**44**	**45**	**46**
45	Arkansas No. 13	22.06	77.94	93	92	6.89	6.81	13112	12917
58	Illinois No 1	18.40	81.60	108	93	8.00	6.89	12178	10535
59	"	18.40	81.60	109	95	8.08	7.04	12178	10535
48	Illinois No. 7 E	10.02	89.98	121	113	8.96	8.37	10667	10021
39	Illinois No. 9 C	15.00	85.00	105	99	7.78	7.33	12385	11713
13	Illinois No. 12 BW	23.85	76.15	81	74	6.00	5.48	12958	11930
52	Illinois No. 19 E	22.05	77.95	105	97	7.78	7.18	12411	11501
53	"	22.05	77.95	112	104	8.30	7.70	12411	11501
54	"	22.05	77.95	101	93	7.48	6.89	12411	11501
55	"	22.05	77.95	98	90	7.26	6.67	12411	11501
9	Illinois No. 29 AW	13.95	86.05	95	84	7.04	6.22	13306	11671
12	Illinois No. 29 B	13.56	86.44	102	96	7.56	7.11	12562	11756
33	Illinois No. 31	9.47	90.53	104	94	7.70	6.96	12024	10921
34	"	9.47	90.53	103	94	7.63	6.96	12024	10921
44	"	11.97	88.03	116	108	8.59	8.00	11995	11158
43	Illinois No. 33	26.85	73.15	124	113	9.19	8.38	10782	9761
37	Indiana No. 1 B	13.13	86.87	133	127	9.86	9.41	11907	11390
36	Indiana No. 5 B	14.79	85.21	110	106	8.15	7.85	12970	12425
38	Indiana No. 6 B	10.48	89.52	103	97	7.63	7.18	12557	11839
10	Indian Territory No. 2 BW	32.11	67.89	93	91	6.89	6.74	13865	13561
11	Indian Territory No. 2 B	15.05	84.95	94	92	6.96	6.82	13196	12912
1	Kansas No. 2 B	.....	.....	83	81	6.15	6.00	12132	11795
40	"	13.53	86.47	97	94	7.18	6.96	11855	11444
21	Maryland No. 2	22.64	77.36	82	79	6.08	5.85	14694	14161
22	"	22.64	77.36	75	71	5.56	5.26	14694	14161
23	"	22.64	77.36	81	78	6.00	5.78	14694	14161
20	"	27.30	72.70	66	65	4.89	4.72	14473	14229
2	Missouri No. 10	13.89	86.11	151	135	11.20	10.00	11588	10310
3	"	13.89	86.11	98	87	7.26	6.44	11588	10310
4	"	13.89	86.11	105	93	7.78	6.89	11588	10310
5	"	13.89	86.11	127	113	9.41	8.37	11588	10310
28	Pennsylvania No. 18	16.64	83.36	73	67	5.41	4.97	14408	13338
29	"	16.64	83.36	82	76	6.07	5.63	14408	13338
30	"	12.02	87.98	68	65	5.04	4.81	14559	13873
31	"	12.02	87.98	69	66	5.11	4.89	14559	13873
46	"	22.54	77.46	80	78	5.93	5.78	14038	13680
24	"	25.38	74.62	69	67	5.11	4.97	14096	13820
25	"	25.38	74.62	69	66	5.11	4.89	14377	13865
32	Pennsylvania No. 19	10.44	89.56	82	81	6.08	6.00	13889	13646
15	"	31.05	68.95	61	60	4.52	4.44	13996	13712
26	Pennsylvania No. 20	15.53	84.47	66	62	4.89	4.59	14064	13198
27	"	15.53	84.47	69	65	5.11	4.82	14064	13198
41	Pennsylvania No. 20 W	17.04	82.96	76	75	5.63	5.56	14069	13896
42	"	17.04	82.96	75	74	5.56	5.48	14069	13896
16	Pennsylvania No. 22	15.01	84.99	70	69	5.18	5.11	13867	13561
17	"	15.01	84.99	67	65	4.96	4.82	13867	13561
18	"	30.83	69.17	69	67	5.11	4.96	13764	13275
19	"	30.83	69.17	68	66	5.04	4.89	13764	13275
14	"	22.96	77.04	65	64	4.82	4.74	13812	13568
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half)	24.55	75.45	79	79	5.85	5.85	12887	12793
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three fourths)	24.20	75.80	79	78	5.85	5.78	12857	12721
57	"	24.20	75.80	93	92	6.89	6.82	12857	12721
35	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half)	13.89	86.11	86	85	6.37	6.30	13569	13387
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth)	19.30	80.70	79	77	5.85	5.70	13431	13185
50	Pennsylvania No. 18 (one-half) and Miscellaneous No. 9 (one-half)	28.05	71.95	83	81	6.15	6.00	12955	12787
51	"	28.05	71.95	81	80	6.00	5.92	12955	12787
7	Virginia No. 5 B	21.07	75.93	89	85	6.59	6.30	13136	12542
8	"	24.07	75.93	79	75	5.87	5.56	13136	12542

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT ST. LOUIS—(*Continued*)

Test No.	Designation of Fuel	Water pounds		Factor of Evaporation	Equivalent Evaporation per hour from and at 212° F. (pounds)	Horsepower Developed	Equivalent Evaporation per hour from and at 212° F. per sq. ft. of Water Heating Surface (pounds)	Mean Load Carried (sq. ft. of radiating surface)	Percentage of Builders' Rated Capacity Developed
		Fed to Boiler	Evaporated into Dry Steam from and at 212° F.						
		49	52	51	53	53.1	54	55	56
45	Arkansas No. 13	4186	4487	1.0720	539	15.6	3.39	1797	57.0
58	Illinois No. 1	3422	3754	1.0970	474	13.7	2.98	1580	50.2
59	"	3809	4159	1.0919	520	15.1	3.27	1733	55.0
48	Illinois No. 7 E	3708	3989	1.0759	499	14.5	3.14	1663	52.8
39	Illinois No. 9 C.	3786	4089	1.0800	493	14.3	3.10	1643	52.2
13	Illinois No. 12 BW	3188	3430	1.0758	416	12.1	2.62	1387	44.0
52	Illinois No. 19 E	3625	3914	1.0798	502	14.6	3.16	1673	53.1
53	"	4482	4886	1.0902	592	17.2	3.73	19 3	62,6
54	"	3325	3599	1.0825	447	13.0	2.81	1490	47.3
55	"	3959	4334	1.0946	554	16,1	3,49	1847	58.7
9	Illinois No. 29 A W	4900	5239	1.0692	665	19.3	4.18	2217	70.4
12	Illinois No 29 B	4134	4423	1.0700	615	17.8	3.87	2050	65.1
33	Illinois No. 31	3960	4407	1.1130	563	16.3	3.54	1877	59.6
34	"	4292	4801	1.1187	594	17.2	3.74	1980	62.9
44	"	4248	4585	1.0794	550	15.9	3.46	1833	58.2
43	Illinois No. 33	3805	4075	1.0710	521	15.1	3.28	1737	55.2
37	Indiana No. 1 B	4915	5399	1.0985	648	18.8	4.08	2160	68.6
36	Indiana No. 5 B	4523	5048	1.1161	600	17.4	3.77	2000	63.5
38	Indiana No. 6 B	3962	4272	1.0782	542	15.7	3.41	1807	57.4
10	Indian Territory No. 2 BW	4866	5198	1.0682	656	19,0	4.13	2187	69.4
11	Indian Territory No, 2 B	5411	5739	1.0606	729	21.1	4.58	2430	77.2
1	Kansas No. 2 B	3433	3686	1.0737	461	13.4	2.90	1537	48.8
40	"	4023	4357	1.0829	528	15.3	3.32	1760	55.9
21	Maryland No. 2	4895	5224	1.0673	653	18.9	4.11	2177	69.1
22	"	4188	4489	1,0719	599	17.4	3.77	1997	63.4
23	"	4260	4581	1.0754	573	16.6	3.60	1910	60.6
20	"	4079	4377	1,0731	556	16.1	3.50	1853	58.8
2	Missouri No. 10	5152	5498	1.0671	718	20.8	4.52	2393	76.0
3	"	3824	4087	1.0688	522	15.1	3.28	1740	55.2
4	"	4036	4356	1.0792	557	16.1	3.50	1857	59.0
5	"	5415	5755	1.0627	708	20.5	4.45	2360	74.9
28	Pennsylvania No. 18	3720	4014	1,0790	502	14.6	3.16	1673	53.1
29	"	4879	5246	1.0752	656	19.0	4.13	2187	69.4
30	"	4404	4722	1.0723	613	17.8	3,86	2043	64.9
31	"	4095	4393	1.0728	549	15.9	3.45	1830	58.1
46	"	4343	4710	1.0845	579	16.8	3.64	1930	61.3
24	"	4209	4520	1,0740	565	16.4	3.55	1883	59.8
25	"	4113	4413	1.0729	552	16.0	3.47	1840	58.4
32	Pennsylvania No. 19	3142	3480	1.1076	529	15.3	3.33	1763	56.0
15	"	3239	3487	1.0765	465	13.5	2.92	1550	49.2
26	Pennsylvania No. 20	4069	4367	1.0733	546	15.8	3.43	1820	57.8
27	"	3829	4126	1.0775	516	15.0	3.25	1720	54.6
41	Pennsylvania No. 20 W	4416	4735	1.0723	606	17.6	3.81	2020	64.2
42	"	2703	2931	1.0844	564	16.3	3.55	1880	59.7
16	Pennsylvania No. 22	3473	3743	1.0776	478	13.9	3.01	1593	50.6
17	"	3531	3816	1.0807	472	13.7	2.97	1573	49.9
18	"	3457	3723	1.0769	465	13.5	2.92	1550	49.2
19	"	3627	3909	1.0777	486	14.1	3.06	1620	51.4
14	"	3844	4132	1.0748	545	15.8	3.43	1817	57.7
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half)	3993	4273	1.0700	519	15.0	3.26	1730	54.9
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths)	4173	4555	1.0915	558	16.2	3.51	1860	59.1
57	"	3698	4042	1.0929	577	16.7	3.63	1923	61.0
35	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half)	3118	3485	1.1177	616	17.9	3.87	2053	65.2
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth)	4308	4636	1.0761	563	16.3	3.54	1877	59.6
50	Pennsylvania No. 18 (one-half) and Miscellaneous No. 9 (one-half)	3860	4158	1.0773	531	15.4	3.34	1770	56.2
51	"	3928	4237	1.0787	530	15.4	3.33	1767	56.1
7	Virginia No. 5 B	5353	5678	1.0608	710	20.6	4.47	2367	75.1
8	"	4270	4544	1.0642	583	16.9	3.67	1943	61.6

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT ST. LOUIS—(*Continued*)

Test No.	Designation of Fuel	Economic Results pounds				Efficiency per cent	
		Equivalent Evaporation from and at 212° F. per pound of Fuel		Fuel per hour per 100 square feet of Radiating Surface (mean load carried during test)		Boiler and Furnace (dry fuel basis)	Plant (fuel as fired basis)
		As Fired	Dry	As Fired	Dry		
		57	58	59	60	61	62
45	Arkansas No. 13	5.77	6.14	5.18	5.12	45.22	43.14
58	Illinois No. 1	4.40	5.32	6.84	5.89	42.19	40.33
59	"	4.76	5.71	6.29	5.48	45.28	43.63
48	Illinois No. 7 E	4.13	4.56	7.28	6.80	41.28	39.80
39	Illinois No. 9 C	4.69	5.18	6.39	6.02	40.39	38.67
13	Illinois No. 12 BW	5.15	5.84	5.84	5.34	43.52	41.69
52	Illinois No. 19 E	4.79	5.39	6.28	5.80	41.94	40.22
53	"	5.27	5 91	5.68	5.27	45.99	44.25
54	"	4.44	4.97	6.78	6.24	38.67	37.28
55	"	5.67	6.33	5.30	4.87	49.25	47.61
9	Illinois No. 29 AW	6.98	8.08	4.29	3.79	58.64	57.75
12	Illinois No. 29 B	6.02	6.59	4.98	4.68	50 66	49.45
33	Illinois No. 31	5.42	6.08	5.54	5.00	48 83	47.93
34	"	5.74	6.46	5.20	4.75	51.88	50.76
44	"	4.74	5.21	6.33	5.89	41.94	41.02
43	Illinois No. 33	4.19	5.36	7.14	6.50	48.01	41.45
37	Indiana No. 1 B	4.89	5.21	6.16	5.88	42.25	41.46
36	Indiana No. 5 B	5.44	5.82	5.50	5.30	43.33	42.28
38	Indiana No. 6 B	5.24	5.70	5.70	5.37	43.84	42.74
10	Indian Territory No. 2 BW	7.06	7.58	4.25	4.16	52.79	50.28
11	Indian Territory No. 2 B	7.79	8.20	3.87	3.79	60.01	58.26
1	Kansas No. 2 B	5.53	5.69	5.40	5.27	45.29	45.28
40	"	5.45	5.86	5.51	5.34	47.74	45.99
21	Maryland No. 2	8.02	8.54	3.77	3.63	56.13	54.69
22	"	8.02	8.41	3.76	3.55	55.27	54.69
23	"	7.05	7.50	4.24	4.08	49.29	48.08
20	"	8.42	8.72	3.56	3.51	58.18	57.15
2	Missouri No. 10	4.75	5.58	6.31	5.64	46.50	44.49
3	"	5.31	6.28	5.63	5.00	52.34	49.74
4	"	5.32	6.27	5.66	5.01	52.25	49.83
5	"	5.55	6.41	5.38	4.79	53.42	51.98
28	Pennsylvania No. 18	6.92	7.56	4.37	4.01	50.67	50.10
29	"	8.05	8.78	3.75	3.48	58.85	58.28
30	"	9.00	9.52	3.33	3.18	63.15	62.65
31	"	7.99	8.52	3.77	3.61	56.51	55.62
46	"	7.21	7.72	4.14	4.04	52 71	50.90
24	"	8.22	8.58	3.67	3.56	58.78	57.44
25	"	8.02	8.52	3.75	3.59	57.23	55.86
32	Pennsylvania No. 19	6.43	6.60	4.65	4.60	45.89	45.50
15	"	7.64	7.96	3.94	3.87	54 92	53.81
26	Pennsylvania No. 20	8.32	9.02	3.63	3.41	61.94	60.88
27	"	7.50	8.12	4.01	3 78	55.76	54.88
41	Pennsylvania No. 20 W	7.97	8.21	3.76	3.71	56.35	55.39
42	"	7.56	7.84	3.99	3.94	53.81	52.54
16	Pennsylvania No. 22	6.81	7.20	4.40	4.33	50.14	48.50
17	"	7.10	7.41	4.26	4.13	51.60	50.56
18	"	6.74	7.41	4.45	4.32	51.99	49.03
19	"	7.09	7.76	4.20	4.07	54.45	51.58
14	"	8.40	9.00	3.58	3.52	62.93	59.79
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half)	6.55	6.94	4.57	4.57	52.01	49.44
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths)	7.08	7.52	4.25	4.19	56.48	53.75
57	"	6.20	6.60	4.84	4.79	49.57	47.07
35	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half)	7.13	7.34	4.19	4.14	52.24	51.43
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth)	7.16	7.61	4.21	4.10	54.72	52.44
50	Pennsylvania No. 18 (one-half) and Miscellaneous No. 9 (one-half)	6.44	6.98	4.69	4.57	52.03	48.64
51	"	6.51	7.09	4.59	4.53	52.85	49.16
7	Virginia No. 5 B	7.98	8.89	3.76	3.59	65.36	61.44
8	"	7.42	8.28	4.07	3.86	60.87	57.13

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT ST. LOUIS—(*Concluded*).

Test No.	Designation of Fuel	Fuel at $1 per 2000 pounds		Thickness of Fire inches	Average Amount of Fuel Fired at each Firing pounds	Average Interval Between Firings hours	Clinkers in Refuse per cent	Black Smoke per cent
		Cost in cents per 100 square feet of Radiating Surface per hour (mean load carried during test)	Cost (in cents) of Evaporating 1000 pounds of Water from and at 212° F.					
		64	65	69	70	71		77
45	Arkansas No. 13	0.2590	8.67	8-16	155	1.66	15	30.3
58	Illinois No. 1	.3420	11.36	8-14	171	1.58	38	25.7
59	"	.3150	10.50	8-16	175	1.60	38	41.2
48	Illinois No. 7 E	.3640	12.10	....	161	1.33	19	40.3
39	Illinois No. 9 C	.3200	10.65	....	145	1.36	28	32.6
13	Illinois No. 12 BW	.2420	9.71	....	74	.92	0	24.1
52	Illinois No. 19 E	.3140	10.44	4-12	163	1.56	0	37.1
53	"	.2840	9.49	8-16	155	1.37	20	30.3
54	"	.3390	11.25	8-16	162	1.61	21	32.5
55	"	.2650	8.82	6-14	153	1.56	0	31.5
9	Illinois No. 29 AW	.2150	7.16	....	62	.66	0	19.2
12	Illinois No. 29 B	.2490	8.31	....	67	.65	26	34.6
33	Illinois No. 31	.2770	9 23	....	163	1.56	13	22.7
34	"	.2600	8.71	....	167	1.61	24	23.7
44	"	.3170	10.55	8-16	161	1.39	46	29.1
43	Illinois No. 33	.3570	11.93	6-18	162	1.30	14	32.8
37	Indiana No. 1 B	.3080	10.22	4-16	158	1.19	48	28.5
36	Indiana No. 5 B	.2750	9.19	4-14	155	1.40	34	32.2
38	Indiana No 6 B	.2850	9.54	8-14	163	1.58	47	32 3
10	Indian Territory No. 2 BW	.2130	7.08	....	74	.79	0	30.4
11	Indian Territory No. 2 B	.1940	6.42	....	67	.71	0	25.2
1	Kansas No. 2 B	.2700	9.04	...	56	.66	44	22.6
40	"	.2760	9.18	6-18	160	1.65	33	26.4
21	Maryland No. 2	.1890	6.24	....	93	1.14	0	14.4
22	"	.1880	6.24	...	140	1.32	0	....
23	"	.2120	7.09	....	163	2.00	0	10.7
20	"	.1780	5.94	....	65	.98	0	1.4
2	Missouri No. 10	.3160	10.52	....	116	.77	29	41.6
3	"	.2820	9.42	....	55	.56	38	51.4
4	"	.2830	9.40	....	55	.52	29	30.6
5	"	.2690	9.01	....	65	.51	30	41.1
28	Pennsylvania No. 18	.2190	7.23	....	145	2.00	0	12.7
29	"	.1880	6.21	....	163	2.00	0	14.2
30	"	.1670	5.56	....	131	1.92	0	25.5
31	"	.1890	6.26	4-12	138	2.00	0	36.8
46	"	.2070	6.94	....	163	2.03	20	26.7
24	"	.1840	6.08	....	138	2.00	0	7.2
25	"	.1880	6.24	....	138	2.00	0	9 2
32	Pennsylvania No. 19	.2330	7.78	....	135	1.64	0	45.7
15	"	.1970	6.54	....	41	.68	0	14.2
26	Pennsylvania No. 20	.1820	6.01	....	131	2.00	0	16.6
27	"	.2010	6.67	....	138	2.00	0	17.7
41	Pennsylvania No. 20 W	.1880	6.27	4-16	148	1.96	0	29.7
42	"	.2000	6.61	6-18	129	1.73	0	....
16	Pennsylvania No. 22	.2200	7.34	....	61	.87	0	25.1
17	"	.2130	7.04	....	60	.89	0	26.7
18	"	.2230	7.42	....	69	1.00	0	23.3
19	"	.2100	7.05	...	138	2.01	0	22.9
14	"	.1790	5 96	....	62	.95	0	16 1
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half)	.2290	7.64	4-18	163	2.06	24	29.9
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths)	.2130	7.06	8-18	161	2.04	24	32 2
57	Pennsylvania No. 18 (one half) and Rhode Island No. 1 (one half)	.2420	8.06	8-16	163	1.75	25	31.4
35	"	.2100	7.01	4-12	162	1.88	0	19.3
49	Pennsylvania No. 18 (three fourths) and Miscellaneous No. 9 (one fourth)	.2110	6.98	....	162	2.06	16	....
50	Pennsylvania No. 18 (one-half) and Miscellaneous No. 9 (one-half)	.2350	7 77	8-16	162	1.96	0	28.9
51	"	.2300	7.68	10-18	163	2.00	0	32.6
7	Virginia No. 5 B	.1880	6.27	....	65	.73	0	16.7
8	"	.2010	6.74	...	123	1.56	0	39 5

TABLE 17

AVERAGE PERCENTAGE OF CO_2, O_2, AND CO FROM 52 TESTS MADE ON FUEL IN HOUSE-HEATING BOILER AT ST. LOUIS

Test No.	CO_2	O_2	CO	Test No.	CO_2	O_2	CO
7	10.1	6.35	0.40	34	7.2	10.9	0.1
8	10.9	5.4	1.02	35	7.8	9.80	.10
9	10.22	7.56	.7	36	7.9	8.3	.96
10	9.74	8.44	.34	37	12.1	4.3	.75
11	7.57	10.0	.68	38	9.3	6.8	.55
12	9.26	8.30	.44	39	8.75	5.45	1.0
13	6.96	11.35	.20	40	8.2	8.86	.53
14	7.0	10.68	.52	41	6.7	10.8	.20
15	5.8	11.30	.18	42	7.1	9.8	.25
16	6.8	11.3	.56	43	6.8	11.4	.4
17	6.8	10.26	.43	44	7.6	9.4	.4
18	7.2	9.85	.65	45	13.3	4.3	.6
19	8.0	8.77	.84	46	10.3	6.75	.65
20	7.13	9.83	.53	47	9.2	9.25	.15
21	8.6	7.25	.51	48	8.3	9.8	.6
22	8.0	6.58	1.62	49	8.1	9.80	.60
23	7.5	7.40	1.28	50	8.6	9.3	.15
24	6.8	11.84	.24	51	9.4	9.0	.60
25	7.0	11.60	.11	52	8.75	7.65	1.50
26	7.6	10.35	.28	53	9.8	6.65	1.0
27	5.8	12.81	.05	54	9.7	6.5	.6
28	7.5	10.75	.46	55	12.5	4.0	.75
29	7.4	10.76	.34	56	9.8	7.10	.40
30	7.4	10.63	.13	57	9.9	7.90	.25
31	6.5	10.40	.30	58	9.3	8.1	.45
32	7.0	10.35	.15	59	9.7	7.4	1.2

APPENDIX C

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE ENGINEERING EXPERIMENT STATION UNIVERSITY OF ILLINOIS*

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Shape of Briquets	Date	Duration of Test hours	Average Pressure				Average Temperature (°F.)		
						Steam gage		Draft (in. of water)		External Air	Boiler Room	Feed Water in Weigh Tank
						Boiler	Receiver	Flue	Over Fire			
				1907	1	10	11	12	13	14	15	16
136	D1	Illinois No. 7 E	Round	June 19.	8.62	4.25	1.87	0.15	0.10	..	..	148.9
137	D2	"	"	"	7.38	4.98	1.58	.16	.06	..	.	158.0
152	D1	Illinois No. 9 C	"	June 28.	7.78	6.39	2.02	.15	.12	74	79	164.5
153	D2	"	"	"	8.02	5.04	1.71	.15	.06	74	79	168.3
154	D1	Illinois N W	"	June 29.	7.97	7.04	2.06	.15	.12	82	83	159.9
155	D2	"	"	"	7.50	3.60	1.32	.13	.03	82	83	161.6
142	D1	Illinois No. 31	"	June 22.	7.35	6.69	2.05	.15	.11	..	..	151.3
143	D2	"	"	"	6.85	5.22	1.67	.15	.05	..	..	153.7
144	D1	"	Square	June 24.	7.93	5.61	1.94	.17	.10	..	..	150.8
145	D2	"	"	"	7.52	6.02	1.70	.22	.04	..	..	144.5
158	D1	Illinois No. 33	Round	July 2.	7.97	6.78	2.05	.15	.12	75	81	165.1
159	D2	"	"	"	8.15	5.34	1.71	.18	.05	75	81	166.0
140	D1	Indiana No. 1 B	"	June 21.	7.97	6.12	2.08	.15	.12	..	..	152.3
141	D2	"	"	"	7.47	5.30	1.68	.18	.04	..	..	157.0
146	D1	Indiana No. 6 B	"	June 25.	8.05	6.32	1.97	.15	.11	78	82	169.1
147	D2	"	"	"	8.00	3.76	1.46	.19	.02	78	82	173.4
148	D1	"	Square	June 26.	8.08	6.59	2.07	.17	.13	77	83	155.8
149	D2	"	"	"	8.25	5.44	1.74	.17	.05	77	83	156.6
138	D1	Missouri No. 10	Round	June 20.	7.95	5.68	1.97	.14	.10	..	..	163.1
139	D2	"	"	"	7.67	4.44	1.86	.20	.05	..	..	162.7
156	D1	Pennsylvania No. 20 W.	"	July 1.	9.17	6.11	2.00	.14	.12	83	88	167.2
157	D2	"	"	"	8.02	5.40	1.60	.14	.07	83	88	169.7
150	D1	Pennsylvania No. 22.	Square	June 27.	8.13	5.72	2.02	.18	.14	74	79	157.5
151	D2	"	"	"	8.45	6.09	1.86	.15	.06	74	79	165.4

*See "21. Data and Results," p. 63.

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS—(*Continued*)

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Fuel as Fired (pounds)				Dry Fuel (pounds)			Total Ash and Refuse from Ash Pit (pounds)	Residual Fuel Removed (pounds)
			Wood	Briquets	Briquets plus Wood	Corrected for residual Fuel	Total Fired	Corrected for Residual Fuel	Actually Consumed (Corrected for Carbon in Ash)		
			20	**21**	**21.1**	**21.2**	**23**	**23.1**	**23.2**	**24**	**25**
136	D1	Illinois No. 7 E.......	6.0	372	374.4	340.5	347.9	316.4	307.4	34.0	82.5
137	D2	"	6.2	335	337.5	318.9	313 6	296.3	272.8	76.0	34.0
152	D1	Illinois No. 9 C.......	10.0	275	279.0	266 2	259.8	247.8	245.2	26.0	27.0
153	D2	"	10.0	375	379 0	363.0	352.9	338 0	325.8	51.0	23.5
154	D1	Illinois No. 30 W......	10.0	255	259.0	251.1	242.6	235 2	233.9	13.0	14,2
155	D2	"	10.0	300	304.0	280.5	284.7	262.7	256.9	23.0	27.7
142	D1	Illinois No. 31.........	6.0	265	267.4	253,9	241.9	229.7	224.0	27.0	24.0
143	D2	"	10.0	275	279.0	269.3	252.4	243 6	232.6	45.0	14.0
144	D1	"	7.5	275	278,0	267.8	254.5	245.2	236.1	35.5	16.0
145	D2	"	7 2	300	302.9	288.9	277.3	264 4	249,7	42.5	20.5
158	D1	Illinois No. 33.........	10,0	260	264.0	254.6	247.5	238.6	235.8	24.0	19.0
159	D2	"	10.5	340	344.2	326.8	322.7	306.3	301.4	34.5	26.5
140	D1	Indiana No. 1 B.......	10.0	275	279.0	268.7	260.0	250.4	240.6	32.5	16.0
141	D2	"	10.0	300	304.0	291.8	283.3	271.9	261.4	43.0	15.5
146	D1	Indiana No. 6 B.......	10.0	265	269.0	261.4	255,3	248.1	244.2	23.0	17,5
147	D2	"	10,0	340	344 0	318.6	326.5	302.4	297.2	33.5	33.0
148	D1	"	10.0	265	269.0	253,2	255.8	240 8	238.8	21.0	31.5
149	D2	"	10.0	340	344.0	326.3	327.1	310.3	303,5	38.5	26.5
138	D1	Missouri No 10,.....	6.0	300	302 4	282.5	282.6	264 0	247.5	57.0	27.0
139	D2	"	6.0	375	377.4	360.2	352.6	336.5	322.7	62.5	32.0
156	D1	Pennsylvania No.20W	10 0	225	229.0	214.6	221 8	207 8	202.7	17.2	16.0
157	D2	" "	11.0	225	229.4	217.4	225.2	210.6	201 9	22 0	14.7
150	D1	Pennsylvania No. 22..	10.0	225	229.0	209.2	220.7	201.6	196.7	20.0	24.0
151	D2	" "	10.0	226	280.0	252.5	269.9	243.4	236.0	25.0	38.0

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT ENGINEERING EXPERIMENT STATION UNIVERSITY OF ILLINOIS—(*Continued*)

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Proximate Analysis of Fuel as Fired per cent				Ash in Ultimate Analysis of Dry Fuel (per cent)	Residual Fuel per cent	
			Fixed Carbon	Volatile Matter	Moisture	Ash		Carbon	Earthy Matter
			26	27	28	29	35	37	38
136	D1	Illinois No. 7 E	....	....	7.07	....	27.43	26.50	73.50
137	D2	"	....	....	7.07	....	27.43	35.34	64.66
152	D1	Illinois No. 9 C	....	....	6.89	....	14.69	35.87	64.13
153	D2	"	....	....	6.89	....	14.69	51.44	48.56
154	D1	Illinois No. 30 W	....	....	6.34	....	8.35	46.47	53.53
155	D2	"	....	....	6.34	....	8.35	71.34	28.66
142	D1	Illinois No. 31	....	....	9.53	....	16.81	40.71	59.29
143	D2	"	....	....	9.53	....	16.81	50.39	49.61
144	D1	"	....	....	8.46	....	16.76	46.16	53.84
145	D2	"	....	....	8.46	....	16.76	49.72	50.28
158	D1	Illinois No. 33	....	....	6.26	....	13.67	40.06	59.94
159	D2	"	....	....	6.26	....	13.67	53.09	46.91
140	D1	Indiana No. 1 B	....	....	6.80	....	14.11	50.81	49.19
141	D2	"	....	....	6.80	....	14.11	62.24	37.76
146	D1	Indiana No. 6 B	....	....	5.08	....	12.27	35.80	64.20
147	D2	"	....	....	5.08	....	12.27	63.04	36.96
148	D1	"	....	....	4.91	....	13.51	40.29	59.71
149	D2	"	....	....	4.91	....	13.51	53.58	46.42
138	D1	Missouri No. 10	....	....	6.56	....	21.57	51.85	48.15
139	D2	"	....	....	6.56	....	21.57	37.98	62.02
156	D1	Pennsylvania No. 20 W	....	....	3.16	....	7.98	85.21	14.79
157	D2	"	....	....	3.16	....	7.98	76.78	23.22
150	D1	Pennsylvania No. 22	....	....	3.61	....	9.68	74.34	25.66
151	D2	"	....	....	3.61	....	9.68	65.23	34.77

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE ENGINEERING EXPERIMENT STATION UNIVERSITY OF ILLINOIS—(*Continued*)

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Ash (per cent)		Dry Fuel per hour (pounds)		British thermal units per pound of Fuel		Moisture in Steam (per cent)
			Carbon	Earthy Matter	Total	Per square foot of Grate Surface	Dry	As Fired	
			40	41	43	44	45	46	47
136	D1	Illinois No. 7 E	18.30	81.70	36.72	8.58	10142	9425	1.02
137	D2	"	21.47	78.53	40.13	6.69	10142	9425	.61
152	D1	Illinois No. 9 C	8.23	91.77	31.84	7.43	11845	11029	.99
153	D2	"	19 44	80.56	42.16	7.03	11845	11029	.90
154	D1	Illinois No. 30 W	9.32	90.68	29.52	6.90	13134	12301	.82
155	D2	"	22.77	77.23	35.03	5.84	13134	12301	1.11
142	D1	Illinois No. 31	17.01	82.99	31.25	7.30	11685	10571	.83
143	D2	"	19.50	80.50	35.56	5.93	11685	10571	.66
144	D1	"	20.30	79.70	30.90	7.22	11574	10595	1.09
145	D2	"	27.41	72.59	35.17	5.86	11574	10595	.72
158	D1	Illinois No. 33	10.26	89.74	29.95	7.00	12573	11786	.95
159	D2	"	12.38	87.62	37.58	6.26	12573	11786	.89
140	D1	Indiana No. 1 B	25.57	74.43	31.43	7.34	12379	11537	.85
141	D2	"	20.85	79.15	36.42	6.07	12379	11537	.69
146	D1	Indiana No. 6 B	14.58	85.42	30.82	7.20	12617	11976	.90
147	D2	"	13.47	86.53	37.81	6.30	12617	11976	.93
148	D1	"	7.87	12.13	29.78	6.96	12319	11714	.76
149	D2	"	14.94	85.06	37 61	6.27	12319	11714	.81
138	D1	Missouri No. 10	21.87	78.13	33.21	7.76	11012	10290	.93
139	D2	"	16.64	83.36	43.89	7.32	11012	10290	.65
156	D1	Pennsylvania No. 20 W	28.87	71.13	22.67	5.30	14262	13811	.98
157	D2	"	38.61	61.39	26.26	4.38	14262	13811	.78
150	D1	Pennsylvania No. 22	23.17	76.83	24.79	5.79	13646	13153	1.08
151	D2	"	27.70	72.30	28.80	4.80	13646	13153	.80

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS—(*Continued*)

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Factor for Correction, Quality of Steam 48	Water pounds: Fed to Boiler 49	Water pounds: Corrected for Quality of Steam 50	Water pounds: Evaporated into Dry Steam from and at 212° F. 52	Factor of Evaporation 51	Water per hour pounds: Equivalent Evaporation from and at 212° F. 53	Water per hour pounds: Equivalent Evaporation from and at 212° F. per square foot of Water-heating Surface 54	Horse-power Developed
136	D1	Illinois No. 7 E	0.9905	1292	1280	1366	1.0677	158.5	3.63	4.59
137	D2	"	.9943	1386	1377	1457	1.0580	197.3	2.69	5.72
152	D1	Illinois No. 9 C	.9907	1215	1204	1266	1.0517	162.7	3.72	4.72
153	D2	"	.9914	1589	1575	1650	1.0477	205.8	2.80	5.97
154	D1	Illinois No. 30 W	.9923	1302	1292	1365	1.0566	171.3	3.92	4.97
155	D2	"	.9895	1234	1221	1287	1.0542	171.6	2.34	4.97
142	D1	Illinois No. 31	.9923	1147	1138	1212	1.0655	165.0	3.78	4.78
143	D2	"	.9938	1346	1337	1421	1.0626	207.5	2.83	6.01
144	D1	"	.9900	1228	1216	1296	1.0660	163.5	3.74	4.74
145	D2	"	.9933	1457	1447	1552	1.0722	206.7	2.82	5.99
158	D1	Illinois No. 33	9910	1270	1259	1323	1.0512	166.0	3.80	4.81
159	D2	"	.9916	1515	1502	1577	1.0497	193.5	2.64	5.61
140	D1	Indiana No. 1 B	.9920	1216	1206	1285	1.0650	161.3	3.69	4.68
141	D2	"	.9935	1281	1273	1350	1.0592	180.7	2.47	5.24
146	D1	Indiana No. 6 B	.9914	1270	1259	1320	1.0469	164.0	3.75	4.76
147	D2	"	9911	1420	1407	1466	1.0420	183.3	2.50	5.31
148	D1	"	.9929	1299	1289	1368	1.0609	169.2	3.87	4.91
149	D2	"	.9923	1669	1655	1754	1.0598	212.5	2.90	6.16
138	D1	Missouri No. 10	.9912	1243	1232	1297	1.0532	163.2	3.74	4.73
139	D2	"	.9939	1557	1546	1630	1.0534	212.5	2.90	6.16
156	D1	Pennsylvania No. 20 W	.9907	1377	1364	1431	1.0489	156.1	3.57	4.53
157	D2	"	.9926	1555	1543	1614	1.0460	201.3	2.74	5.84
150	D1	Pennsylvania No. 22	.9899	1264	1251	1325	1.0590	163.0	3.73	4.73
151	D2	"	.9924	1689	1676	1761	1.0506	208.4	2.84	6.04

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE ENGINEERING EXPERIMENT STATION UNIVERSITY OF ILLINOIS—(*Continued*)

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Mean Load Carried		Percentage of Builder's Rated Capacity Developed (per cent)	Economic Results (pounds)			
			Square Feet Radiating Surface	Square Feet of Radiating Surface plus Radiating Surface of Boiler		Equivalent Evaporation from and at 212° F. per pound of Fuel		Fuel per hour per 100 square feet of radiating Surface (mean load carried during test)	
						Fuel as Fired	Dry Fuel Consumed	As Fired	Dry
			55	55.1	56	57	58	59	60
136	D1	Illinois No. 7 E	528	566	66.0	4.01	4.44	7.48	6.95
137	D2	"	658	761	61.2	4.57	5.34	6.57	6.10
152	D1	Illinois No. 9 C	542	580	67.8	4.76	5.16	6.31	5.87
153	D2	"	686	789	63.8	4.55	5.06	6.60	6.15
154	D1	Illinois No. 30 W	571	609	71.4	5.44	5.84	5.52	5.17
155	D2	"	572	675	53.2	4.59	5.01	6.54	6.12
142	D1	Illinois No. 31	550	588	68.8	4.77	5.41	6.28	5.68
143	D2	"	692	795	64.3	5.28	6.11	5.68	5.14
144	D1	"	545	583	68.2	4.84	5.49	6.19	5.67
145	D2	"	689	792	64.1	5.37	6.22	5.58	5.10
158	D1	Illinois No. 33	553	591	69.2	5.20	5.61	5.77	5.41
159	D2	"	645	748	60.0	4.83	5.23	6.22	5.83
140	D1	Indiana No. 1 B	538	576	67.2	4.78	5.34	6.27	5.85
141	D2	"	602	706	56.0	4.63	5.16	6.49	6.05
146	D1	Indiana No. 6 B	547	585	68.3	5,05	5.41	5.94	5.64
147	D2	"	611	714	56.8	4.60	4.93	6.52	6.19
148	D1	"	564	602	70.5	5.40	5.73	5.55	5.28
149	D2	"	708	812	65.8	5.38	5.78	5.58	5.31
138	D1	Missouri No. 10	544	582	68.0	4.59	5.24	6.53	6.10
139	D2	"	708	812	65.9	4.53	5.05	6.63	6.20
156	D1	Pennsylvania No. 20 W	520	558	65.0	6.67	7.06	4.50	4.36
157	D2	"	671	774	62.4	7.42	7.99	4.04	3.91
150	D1	Pennsylvania No. 22	543	581	67.9	6.33	6.74	4.73	4.56
151	D2	"	695	798	64.6	6.97	7.46	4.30	4.15

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS—(*Concluded*)

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Efficiency per cent		Cost (in cents) per 100 sq. ft. of Radiating Surface per hour (mean load carried during test) *a*	Cost (in cents) of Evaporating 1,000 lb. of Water from and at 212° F. *a*	Average Amount of Fuel Fired at each Firing (pounds)	Average Interval hours		Maximum Interval of Maintaining 2 lb. or more Steam Pressure without Attention (hours)
			Boiler and Furnace 61	Plant 62	64	65	70	Between Firings 71	Between Times of Shaking and Raking 72	73
136	D1	Illinois No. 7 E............	42.28	41.09	0.374	12.47	75	1.53	1.02	2.00
137	D2	"	50.85	46.83	.374	10.94	45	1.04	.76	1.77
152	D1	Illinois No. 9 C...........	42.07	41.69	.328	10.50	75	2.13	2.13	2.22
153	D2	"	41.26	39.84	.316	10.99	75	1.76	1.77	2.22
154	D1	Illinois No. 30 W..........	42.94	42.71	.330	9.19	75	2.40	2.40	2.55
155	D2	"	36.84	36.04	.276	10.89	75	1.74	1.74	2.37
142	D1	Illinois No. 31..............	44.72	43.58	.327	10.48	75	2.31	2.31	2.38
143	D2	"	50.50	48.24	.314	9.47	75	2.13	2.13	2.73
144	D1	"	45.81	44.12	.284	10.33	75	2.52	2.52	2.60
145	D2	"	51.90	48.95	.310	9.31	75	2.01	2.01	2.25
158	D1	Illinois No. 33..	43.09	42.61	.279	9.62	75	2.61	2.61	2.83
159	D2	"	40.17	39.58	.289	10.35	75	1.91	1.91	2.62
140	D1	Indiana No. 1 B............	41.66	40.02	.311	10.46	75	2.21	2.21	2.22
141	D2	"	40.26	38.76	.314	10.80	75	1.94	1.94	2.05
146	D1	Indiana No. 6 B............	41.41	40.73	.325	9.90	75	2.54	2.54	3.03
147	D2	"	37.74	37.10	.297	10.87	75	1.89	1.89	2.48
148	D1	"	44.92	44.52	.326	9.26	75	2.73	2.81	3.62
149	D2	"	45.31	44.36	.278	9.29	75	2.14	2.14	1.83
138	D1	Missouri No. 10..	45.96	43.08	.279	10.89	75	1.91	1.91	2.00
139	D2	"	44.29	42.52	.327	11.04	75	1.42	1.46	1.67
156	D1	Pennsylvania No. 20 W...	47.81	46.64	.332	7.50	75	3.25	3.25	3.60
157	D1	"	54.11	51.89	.225	6.74	75	3.12	3.13	3.35
150	D1	Pennsylvania No. 22......	47.70	46.48	.202	7.90	75	3.44	3.44	3.68
151	D2	"	52.80	51.18	.215	7.17	75	2.51	2.52	2.17

a Based on fuel as $1 per 2000 lb.

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print*).

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905. (*Out of print*)

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Bulletin No. 22. Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. 1908.

Bulletin No. 23. Voids, Settlement and Weight of Crushed Stone, by Ira O. Baker. 1908.

Bulletin No. 24. The Modification of Illinois Coal by Low Temperature Distillation, by S. W. Parr and C. K. Francis. 1908.

Bulletin No. 25. Lighting Country Homes by Private Electric Plants, by T. H. Amrine. 1908.

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Bulletin No. 27. Tests of Brick Columns and Terra Cotta Block Columns, by Arthur N. Talbot and Duff A. Abrams. 1909.

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Bulletin No. 29. Tests of Reinforced Concrete Beams: Resistance to Web Stresses, by Arthur N. Talbot. 1909.

Bulletin No. 30. On the Rate of Formation of Carbon Monoxide in Gas Producers, by J. K. Clement, L. H. Adams, and C. N. Haskins 1909.

Bulletin No, 31. Fuel Tests with House-heating Boilers, by J. M. Snodgrass. 1909.

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 32 MARCH 1909

THE OCCLUDED GASES IN COAL

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AND

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I. INTRODUCTION

Experimental studies on coal have been carried on for some time in the Laboratory of Industrial Chemistry at the University of Illinois. A number of topics have been taken up, such as Weathering,[1] Distillation at Low Temperature,[2] Pure Coal,[3] Classification,[4] The Composition and Analysis of Illinois Coal,[5] etc., etc.

These studies, while conducted as independent lines of work, are so interrelated that not infrequently the facts brought out under one division have aided very materially in the interpretation of results obtained under another heading. Especially, also, has it been found that each one of the original topics has subdivided so that the main subjects have grown in number. This is well illustrated in our studies on the weathering of coal. As the facts accumulated in that work, it very soon became evident that an initial loss of heat values occurred in the first few days after release of the coal from the seam, which could not be credited to oxidizing conditions. This naturally led to the study of the topic which we have for convenience designated the Deterioration of Coal, because it is not strictly a weathering process. A preliminary report on this phase was made in Bulletin No. 17 of the Engineering Experiment Station. Additional information on this topic was also published in an article contributed to the Journal of the American Chemical Society,[6] showing conclusively the fact that a positive exudation of combustible gases occurs in freshly mined coal. From the development of this fact there naturally arose the necessity of inaugurating an independent series of experiments which has resulted in this special study of the occluded gases in coal.

Another subdivision of the work on weathering naturally arose in connection with the storage of coal. For a complete understanding of all phases of this topic it seemed essential that we add to our information concerning the causes underlying spontaneous combustion. As a means for promoting this latter end it was thought that a study of the occluded gases, their composition, behavior, interreactions, etc., would contribute much needed information upon this very important point. Some of the results presented herewith bear upon this topic in quite an unexpected manner, and particular attention is called in the accompanying tables to the marked avidity of coal for oxygen.

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[1] Bulletin No. 17, Univ. of Ill. Eng. Exp. Sta.

[2] Bulletin No. 24, Univ. of Ill. Eng. Exp. Sta.

[3] Trans. Am. Inst. Min. Engrs., July, 1907.

[4] Jour. Am. Chem. Soc. Vol. 28, p. 1425.

[5] University Studies, Vol. 1, No. 7.

[6] Jour. Am. Chem. Soc., Vol. 30, p. 1027.

Again, it is an interesting fact to note that in the studies as outlined in Bulletin No. 24 on the low temperature distillation of coal, a subdivision of that topic came about as a natural result of certain experiments which indicated an unexpectedly low temperature at which active oxidation was effected. A detailed study was therefore made of oxidation conditions, the temperatures at which chemical action was set up, and the relation between the external temperature and the speed of such reactions.[1] The fact was soon developed that oxidation took place at much lower temperatures than had been supposed. It is very evident, therefore, from a simple statement of these facts that we have developed still another independent topic as a result of the study of oxidation temperatures on one hand and the experiments connected with the occluded gases on the other. This work has, therefore, been taken up under the heading of Spontaneous Combustion. Here, it will be noted, the behavior of the occluded gases plays an important part, and it was believed that the facts which might develop from such a study would contribute materially to our understanding of oxidation in this more active form. Already the results of this line are beginning to give promise of information which will be of special value, and will at least contribute to a better understanding of this difficulty, if indeed there will not develop practical suggestions as to methods for avoiding the danger and loss attending the firing of coal in storage. It is hoped that this work will be sufficiently advanced to warrant at least a preliminary report during the current year.

Concerning the work here outlined on the occluded gases, it should be said that the study is not to be considered by any means complete. The facts obtained make a well rounded unit, as a preliminary study, and since a considerable time must elapse before the final round of work can be completed, it has seemed advisable to publish the results that have been thus far worked out with much skill and patience by Mr. Barker.

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[1] Bulletin No. 24, Univ. of Ill. Eng. Exp. Sta.

Provision has been made by the Engineering Experiment Station for again taking up this work.

Thanks are due also to Dr. H. Foster Bain, Director of the Illinois State Geological Survey, for cooperation in this and the other investigations on Illinois coal. It is directly due to assistance from these two sources that the coal studies carried on in this laboratory have been made possible.

II. BIBLIOGRAPHY

All varieties of coal, as well as peat, are known to contain occluded or mechanically enclosed gases. Their nature and amount are dependent upon the structure and age of the coal and the conditions of weathering to which it has been exposed. A large part of these gases escapes when the coal is first exposed in the seam. At times the immense volume and explosive or poisonous nature of the escaping nitrogen, carbon dioxide, and methane derivatives, make it either dangerous or impossible to mine the coal. However, a portion is retained within the coal only to be given up by continued exposure and at increased temperatures.

Within the past thirty years numerous investigations of the character of the gases occluded in European coals have been made. The first investigation of this sort was conducted by Websky[1], who made an examination of the gases evolved by peat.

He found this gas to consist of nitrogen, 53.67; carbon dioxide, 2.97; and methane, 43.36. Later, Von Meyer[2] made quite an extensive examination of various German coals. The method of extraction in these experiments was as follows. The coal in nut-sized pieces was placed in a flask and covered with freshly boiled water. The flask was securely stoppered with a rubber cork, having an outlet to a bell for collecting the gas. On heating, the gas enclosed in the coal was given off and replaced a corresponding volume of water in the collector. The first series of experiments was upon Zwickan coal, both in the fresh state and after exposure, as shown in Table I.

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[1] Jour. prakt. Chemie., Vol. 92. p. 76, (1861).

[2] Jour. prakt. Chemie., Vol. 5, p. 144, (1872).
Abs. Jour. Chem. Soc. Vol. 10. p. 798, (1872)

TABLE I

GASES IN ZWICKAN COAL

I, III, and V, coal fresh from seam.
II same as I, weathered for 5 years.
IV “ “ III, “ “ 1½ years.
VI “ “ V, “ “ 5 years.

	I Fresh	II Weathered	III Fresh	IV Weathered	V Fresh	VI Weathered
Vol. per 100 g.	38.00	18.20	25.50	18.60	52.80	13.60
CO_2	2.42%	16.70%	4.02%	2.25%	.60%	7.62%
O	2.51	4.90	.62	.70	.0	2.44
C_2H_4		1.47				.96
CH_4	71.90	3.17	45.00	73.16	51.40	15.88
C_2H_6		18.61				22.35
N	23.17	55.15	50.36	23.89	48.00	50.75

A series of coal from Bochum, both fresh and weathered, was also examined, with results as shown in Table II.

TABLE II

GASES IN BOCHUM COAL

	I Fresh	II Weathered	III Fresh	IV Weathered	V Fresh	VI Weathered
Vol. per 100 g.	50.6	43.2	43.3	41.2	59.2	43.6
CO_2	4.87%	11.12%	2.18%	15.84	4.82%	7.68%
O	2.66	2.88	2.12	3.06	1.99	2.24
CH_4	16.65	7.40	25.19	6.57	31.57	3.31
N	75.82	78.60	70.51	74.53	60.62	86.77

	VII Fresh	VIII Weathered	IX Fresh	X Weathered	XI Fresh	XII Weathered
Vol. per 100 g.	54.4	39.2	54.5	39.6	42.0	36.4
CO_2	1.30%	4.35%	2.02%	2.15%	3.72%	8.49%
O	1.60	3.35	.90	3.14	.39	3.57
CH_4	30.25	11.12	10.65	3.43	5.70	.0
N	66.85	81.18	86.43	91.28	90.19	87.94

The author notes the increase in the ratio of nitrogen content over that of ordinary air. He maintains that the nitrogen has been enclosed in the coal during its formation, that a part results from the reactions in the formation, and that another part is due to the air taken into the material of the coal, this last portion being the residue from the air, the oxygen having been absorbed by the coal with the formation of water and CO_2. He refers to the recent study upon the oxidation of coal by Richter,[1] who maintains that the resulting compound is principally water, while only comparatively small amounts of CO_2 were formed. This theory seems to be borne out by the above analyses in which the CO_2 has never completely replaced the oxygen of the air. It is also noted that one of these coals, very high in sulphur, gave high CO_2, which is in accordance with Richter's[2] statement, that increase in the content of pyrite, facilitates the absorption of oxygen. The presence of higher hydrocarbons of the methane series, also ethylene, indicates a possible rise in temperature within the coal during exposure, due to the absorption of oxygen with a resulting destructive distillation.

Later, this same author[3] has investigated a number of English coals. He found in none of these any gases absorbable by fuming sulphuric acid, and methane was the predominating combustible gas. O. Kolbe,[4] in the same year, reported several analyses of lignites. Von Meyer has also made a second series of investigations on German coals.[5]

In 1875 Thomas[6] began extensive tests upon the gases occluded in English coals. He devised an entirely different method for removing the gases. The coal was placed, in one large piece, in a glass tube which was sealed to a Sprengel mercury pump. When a vacuum had been established, the tube containing the coals was immersed in water at 100° C., and the gases removed by the pump. The rapidity of evolution of the gas depends upon the hardness of the coal and the quantity contained. The following table gives the results of Thomas's first series of experiments.

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[1] Chem. Centralblatt, 1870, p. 245, 543.

[2] Chem. Centralblatt, 1870, p. 543.

[3] Jour. prakt. Chemie., Vol. 6, p. 407, (1872).
Abs. Jour. Chem. Soc., Vol. 10, p. 801.

[4] Jour. prakt. Chemie., Vol. 6, p. 79, (1873).

[5] Jour. prakt. Chemie., Vol. 6, p. 389, (1873).

[6] Jour. Chem. Soc., Vol. 13, p. 793, (1875).

TABLE III

Gases in English Coals

		Cc. per 100 grams	CO_2	O	CH_4	N
1	Bituminous	55.9	36.42%	.80%	.00%	62.78%
2	"	61.2	16.77	2.72	.40	80.11
3	"	55.1	5.44	1.05	63.76	29.75
4	Semi-bituminous	73.6	12.34	.64	72.51	14.51
5	Steam coal	194.8	5.04	.33	87.30	7.33
6	"	250.1	13.21	.49	81.64	4.66
7	"	218.4	5.46	.44	84.22	9.88
8	"	147.4	18.90	1.02	67.47	12.61
9	"	375.4	9.25	.34	86.92	3.49
10	"	149.3	11.35	.56	73.47	14.62
11	"	215.4	5.64	.54	82.70	11.12
12	"	24.0	22.16	6.09	2.68	69.07
13	"	39.7	9.43	2.25	31.98	56.34
14	"	555.5	2.62		93.13	4.25
15	"	600.6	14.72		84.18	1.10

The second series of analyses of Thomas was on the gases evolved from fans or "blower gas". Some previous work[1] has been done upon this class of gases and Thomas's work confirmed these results. Most of these samples contained between 94 and 97 per cent of methane.

In another publication Thomas[2] gives the results of the examination of samples of lignites. He concludes, as in the case of a previous author,[3] that lignites oxidize readily and always contain a small percentage of CO.

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[1] Bischof, Edinburgh New Phil. Jour, Vol, 29, p. 39. Vol. 30. p. 127, (1840).
Bunsen, Petersburg Akad. Bull, Vol. 14, p. 59.
Playfair, Memoirs of the Chemical Soc., Vol. 2, p. 7.
Graham, Memoirs Geol, Sur. Gt. Britain, Vol. 1, p. 460.

[2] Jour. Chem. Soc., Vol. 17, p. 146, (1877).

[3] Varretropp, Chem. Centralblatt, 1865, p. 953.

TABLE IV

GASES PRESENT IN LIGNITES

I Bohemian lignite
II Earthy lignite
III Bovey Heathfield lignite (at 100° C.)
IV Mineral resin

	I	II	III	IV
Vol. per 100 g.	------	------	59.9	21.4
CO_2	96.41%	83.99%	89.53%	88.24%
O	.32	.65	------	.23
CO	1.20	1.04	5.11	7.90
CH_4	trace	------	.33	.47
N	2.17[1]	14.91	5.03	3.16

[1] Adds to 100.10 per cent in the original manuscript.

A series of experiments by Thomas on cannel coals and jets was reported[2] in the same year.

TABLE V

ANALYSES OF CONTAINED GASES IN CANNEL COALS AND JET

I Wigan cannel coal
II " " "
III Scotch " "
IV Scotch cannel coal
V Whitehill cannel shale
VI Whitby jet

	I	II	III	IV	V	VI
Vol. per 100 g.	42.13	35.06	16.80	55.70	55.70	30.20
CO_2	6.44%	9.05%	53.94%	84.55%	68.75%	10.93%
CH_4	80.69	77.19				
C_2H_6	4.75	7.80			2.67	
C_4H_{10}				.91*		86.90
N	8.12	5.96	46.06	14.54	28.58	2.17

*C_3H_8

The noticeable feature in the gases extracted from these cannel coals is the high percentages of C_2H_6 and the absence of oxygen.

Bedson[3] has reported the first analyses upon the gases extracted from coal dusts and found that they showed a general resemblance to those removed from coal and that all the combustible constituents consisted of olefiant gases and methane derivatives.

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[2] Jour. Chem. Soc., Vol. 15, p. 144, (1876).

[3] Trans. North of Eng. Inst. Min. & Mech. Eng., Vol. 37, p. 245, (1888).
Abs. Jour. Soc. Chem. Ind., Vol. 7, p. 729, (1888).

Several years later Bedson[1] published results of amounts of gas given off when coals were heated to 100°C. for 100 hours. Fine coal gave about 300 cu. ft. of gas per ton and of this gas one-sixth was CH_4. Upon reducing these samples further to dust, more gas (20 cu. ft. per ton) was given off, of which 18 per cent was CH_4.

McConnell[2] investigated several seams of English coals as to their content of enclosed gases. Particular attention was paid to the nature of the paraffin hydrocarbons extracted from these coals. One of these analyses from a mine where an explosion had recently taken place showed CO_2, 1.7, 0, 1.0; methane, 88.7; nitrogen, 8.7. The author concludes that the deeper seams yield coals containing combustible gas and CO_2 while the younger ones contain more CO_2 and less combustible gases.

Broockmann[3] criticizes the results of Bedson and McConnell, saying that explosions of dust are not dependent upon the gaseous content of the same. He also states that rubber stoppers will not stand a vacuum, thereby diluting the gas with the products of reactions at high temperatures between the air that has leaked in and the coal.

Bedson[4] has replied to Broockmann's criticism and maintains that his apparatus was air-tight, as all rubber joints were coated with a vacuum-proof cement. He also states that the Austrian Fire-damp Commission has corroborated his statements in regard to the relation of enclosed gases to the inflammable nature of dusts. The author notes the absorption of oxygen by samples exposed in the laboratory, and in this way accounts for the high oxygen-nitrogen ratio in some of his samples.

The latest experimental work upon gases occluded in coal has been conducted by Trowbridge,[5] who compared the gases in fresh coal, "mother of coal", surface dust, and dust from timbers. He concludes that his data show the absorption of gases from the

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Jour. Soc. Chem. Ind. Vol. 11, p. 882, (1892).

[2] Jour. Soc. Chem. Ind. Vol. 13, p. 25, (1894).

[3] Trans. North of Eng. Inst. Min. & Mech. Eng. Vol. 52, p. 16, (1902).
Abs. Jour. Soc. Chem. Ind., Vol. 22, p. 86, (1903).

[4] Trans. North of Eng. Inst. Min. & Mech. Eng., Vol. 52, p. 25, (1902).
Abs. Jour. Soc. Chem. Ind., Vol. 22, p, 86,(1903).

[5] Jour. Soc. Chem. Ind., Vol. 25, p. 1129, (1906).

air, preferably oxygen. Two analyses of fresh and exposed coal are given.

	Fresh	Exposed
CO_2	1.65%	1.18%
O	8.79	23.80
CH_4	44.60	3.58
N	44.76	71.44

Clark[1] upon summing up most of the data upon this subject comments upon the inability to make any comparisons of the results at hand, as all samples represented some loss in transit from mine to laboratory. Of course this loss is dependent upon the structure of the coal and upon the time occupied in transit.

In view of the fundamental relation it bears to a fuller understanding of the subject of alterations in coal, whether in transit or storage, this study of the composition, behavior, and reactions of the occluded gases has been undertaken.

III. Scope of Experimental Work

The experimental work may be conveniently described under the following headings:

1. The construction of apparatus for evacuating the samples.
2. The construction of apparatus for exact gas analysis.
3. The construction of apparatus for collecting samples and devising methods for making collections of coal and the occluded gases.
4. The analysis of the last portion of air and enclosed gases in several samples of coal that had been exposed outside for periods varying from two to fifteen months.
5. The analysis of the last portion of air and the enclosed gases in four sections of a vertical core cut from a pile of screenings that had been exposed outside for fifteen months.
6. The analysis of the gas that had surrounded samples kept in jars for a year; these samples had been previously kept sealed tight for one year, then were transferred to separate jars.
7. The analysis of gas that surrounded samples that had been sealed as soon as they came from the mine.

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[1] Bull. U. S. Geol. Surv., No. 330, p. 660.

8. The analysis of the last portion of air and the enclosed gases from a set of samples of drillings sealed at the mines.

9. The analysis of the last portion of air and the enclosed gases from a set of face mine samples that had been stored in the laboratory for two years. This set of samples corresponded as to mine location with the set described in (8).

10. Miscellaneous analyses of gases from samples used for experiments upon the absorption of oxygen by coal.

IV. Description and Manipulation of Apparatus

The apparatus used for the removal of the occluded gases from the samples of coal consisted of a modified form of the Boltwood mercury air pump, as used by Cady and McFarland[1] in the determination of helium in natural gas, and is shown in Fig. 1. *A* is a side neck funnel for holding mercury. *B* is a stopcock to regulate the feed of the mercury flowing from *A* through *C* and producing a vacuum through *G*, *H*, etc. *D* is a 300 cc. bell jar supplied with a stopcock and is used to collect the gases brought down through *C* by the mercury column. *E* is the outlet of the tube for the return lift for the mercury. *L* is the overflow hole in the mercury tank *M* and keeps *E* from becoming sealed during the operation of the pump. *F* is the return lift to the reservoir *A*, which is connected to an ordinary filter pump through *K*. *G* is a drying U-tube of alternate lengths of phosphorus pentoxide (P_2O_5) and glass wool having ground glass joints to *C* and *H*, the latter being a drying tower of calcium chloride. At *I*, the outlet tube to *H*, a wide end is made in the tubing to admit the constricted tips of the coal sample containers of which *J* is a representation. This joint at *I* is made with rubber resin (Khotinsky) cement.[2] In operating the pump the stopcock *N* is closed and *O* is opened so that the train *G* and *H* can be completely evacuated before any gas from the coal container is admitted. Mercury is allowed to flow from *A* through *C* and out into *M*, the amount being regulated at the cock *B*. While the train is being evacuated, *D* is left empty with the stopcock open or is removed altogether. As *M* fills, the suction at *K* draws mercury from the surface at *E* and returns it to the reservoir *A*. Should the mercury come through *C* too fast, a seal will be formed at *E*. To prevent this an overflow is provided at *L*, and *E* is so regulated that it is on a level with the lowest point of *L*. In order to further prevent a stoppage at *E*, the mouth of this tube was filled with fine iron wire at first, but later a constriction was made at the bend *U* and this kept too much mercury from passing up at a time. When a vacuum had been produced in the train, a solid column remained in *V* and after shutting off the pump connected to *K*, the column *V* should read within 1 or 2 millimeters of barometric height. The scale *S* facilitated the taking of barometer readings, as it was graduated in millimeters above the outlet into the tank *M*. The bell jar *D* is now filled with mercury by pouring into *M* and applying the filter pump to the outlet of *D* at *O*. After completely filling the

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[1] Jour. Amer. Chem Soc., Vol. 29, p. 1523, (1907).

[2] Jour. Amer. Chem. Soc., Vol. 30, p. 20, (1908).

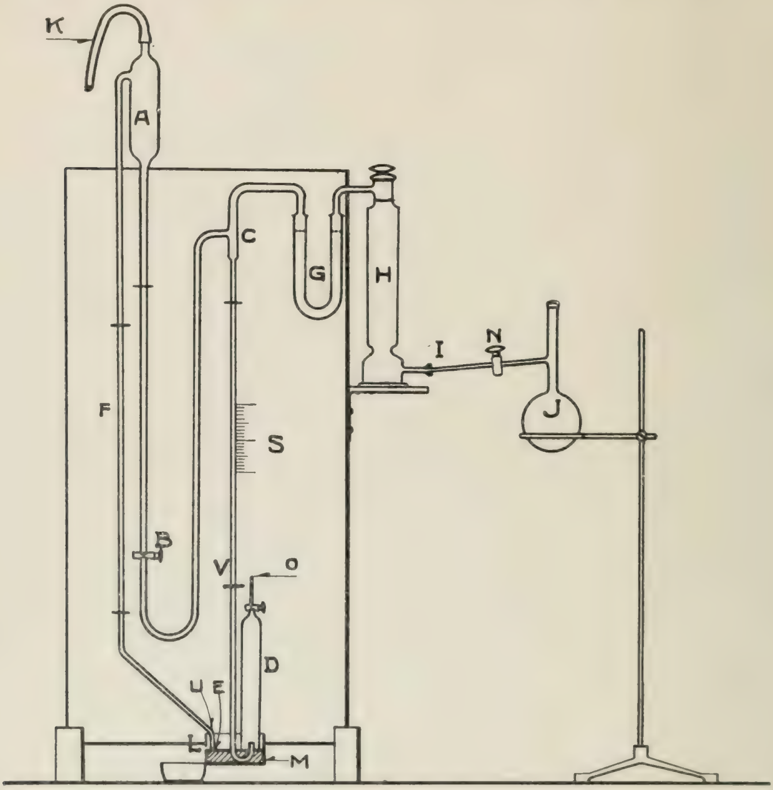

FIG. 1

holder *D* the mercury pump is again started and *N* is opened to allow the gas from *J* to be removed. As this gas comes down *V*, it collects and displaces mercury in *D*. When the column shows approximately barometric height on *S*, the pump is stopped and the gases are transferred from *D* and analyzed.

The apparatus used for gas analysis consisted of a regular set of Hempel's pipettes using an explosion pipette for hydrocarbons. All volumes of gas were measured by means of the Hempel[1] compensating burette shown in Fig. 2. The arrangement and operation of this burette are described by Hempel as follows:

"The instrument consists of the graduated measuring tube *A*, the correction tube *B*, the manometer tube *F*, and the level bulb *G*. The measuring tube and leveling bulb are mounted in suitable iron feet. The measuring tube and the correction tube stand in the wide glass cylinders *C*, which are filled with water to insure that these two tubes are at all times at the same temperature..........

"The correction tube *B* and the manometer tube *F* are made from simple glass tubes fused together in the form shown in the cut; *g* is a small capillary tube. The manometer tube is U-shaped, and is somewhat widened at *k* and *i*, these two widened portions having marks scratched on the glass at exactly the same height. The manometer tube is joined to the measuring tube by means of a piece of rubber tubing connecting the end of the capillary *l* with the tube *a* of the stopcock. The reason for making the manometer tube so long lies in the fact that otherwise, if the apparatus is carelessly handled, the mercury might easily be driven from the manometer tube into the burette or the correction tube. With the arrangement shown in the figure this is almost impossible, since the difference in pressure must be more than half an atmosphere before the mercury can pass over into either tube.........

"Before proceeding with the analysis, the volume of the manometer tube from the mark *k* to the point *a* must be ascertained. To do this, draw over the mercury in the manometer until it reaches *a*, then turn the stopcock *D* to connect with the capillary *b*, and now draw any desired volume of air into the burette. Leaving the stopcock open, read off this volume of air on the scale of the burette, the air here being, of course, under the pre-

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[1] Hempel,—Dennis, Gas Analysis, 3rd Edition, p. 60.

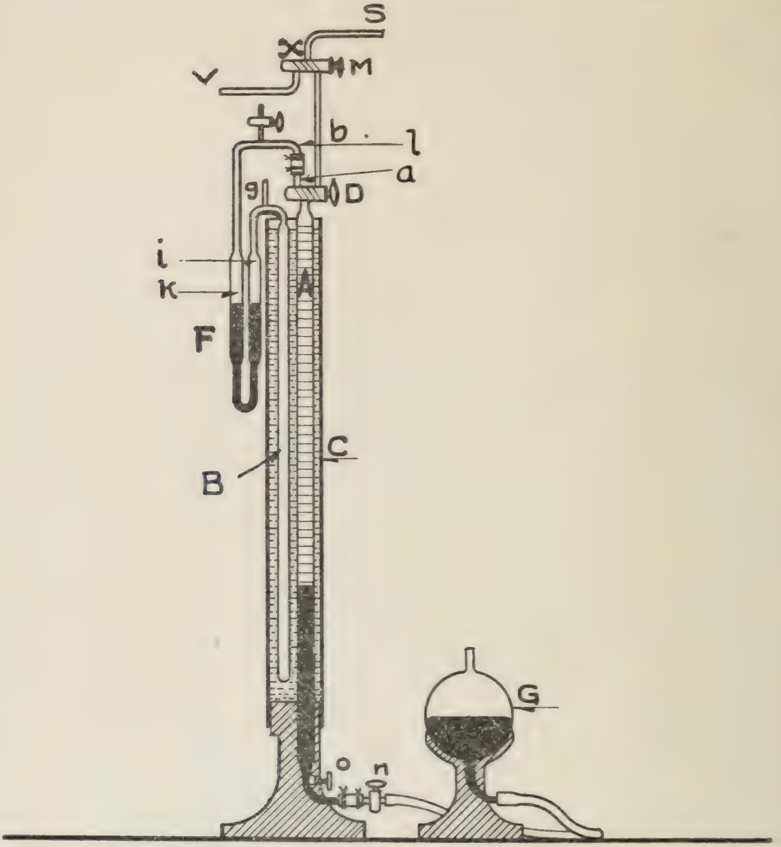

FIG. 2

vailing pressure of the atmosphere. Turn stopcock *D* so that the burette communicates with the manometer tube, and drive the air over into this latter tube until the mercury in it stands at equal height in its two branches; that is, at the marks on *k* and *i*. The difference between the two readings on the measuring tube, provided the tube *g* remains open, gives the volume of the manometer from the mark on *k* up to *a*. . . . .

''In many cases it is highly desirable to arrange the apparatus so that the reading on the measuring tube *A* corresponds directly to volumes at 0° C. and 760 mm. pressure. To accomplish this, a piece of rubber tubing is slipped over the end of the capillary tube *g* and fastened firmly in place by a wire ligature. By lowering the level-bulb, mercury is drawn over into the manometer tube until it reaches the capillary l, and the burette is then allowed to stand for two hours in a room of fairly constant temperature. The stopcock D is then opened so that the contents of the burette are in free communication with the atmospheric air. As soon as one is convinced that all parts of the apparatus are at the same temperature, the gas volume in the burette is read exactly, and the temperature and barometric pressure are noted. The thermometer and barometer should stand in the same room with the apparatus. The stopcock D is closed and the volume which the gas would occupy at 0° C. and 760 mm. barometric pressure is now calculated.

Example: The gas volume is 97 ccm., the barometric pressure 753.3 mm. and the temperature 8.75° C. The space from k to a in the manometer has previously been determined and found to be 1.8 ccm. The tension of the water vapor at 8.75° C. is 8.4 mm.

"If b represents the observed barometric pressure, t the temperature, e the tension of water vapor at that temperature, and V the observed volume, the volume V_0 which the gas would occupy under standard conditions may be calculated from the following formula:—

$$V_0 = V \frac{b - e}{760\,(1 + 0.00367\,t)}$$

In the above example this volume is 92.1 ccm.

Since, however, in making measurements with the correction tube, the gas fills the space from k to a, this volume must be subtracted from the above results:—

$$92.1 - 1.8 = 90.3 \text{ ccm.}$$

"In order now to adjust the gas volume in the correction tube so that readings of volumes in the burette will be reduced at once to standard conditions, the stopcock D is turned so that the burette communicates with the manometer tube, and the gas volume in the burette is compressed by raising the level-bulb G to the volume which it has been calculated that it would occupy at 0° C. and 760 mm. pressure. The mercury in the manometer tube is, of course, forced out of equilibrium by this operation. Air is now blown into the correction tube through the rubber tube at g until the mercury stands at the same height in the two branches of the manometer tube, and the rubber tube is then closed by means of a strong pinchcock placed directly above the end of *g*."

In reading the volumes of gas in the burette, the mercury was always drawn over to *a* and left there while an absorption was being made. The extra stopcock *M* does away with any correction for the connection capillary tube *S*. Whatever absorbent is to be used is driven up from the pipette through *S* to *x*. *M* is then turned so that it connects with *b*, the gas being driven through *S* into the pipette. On returning, the absorbent is brought up to *x* and *M* and *D* are closed. The level at *k* and *i* is established and the volume read. To all readings the volume from *k* to *a* must be added to get the total gas in the burette. *M* is now turned so that the solution in *S* can be washed out through *Y* and the next absorbing pipette is attached.

The containers for samples consisted of the flasks such as *J*, Fig. 1, Putman fruit jars and Mason fruit jars. All the samples for removal of enclosed gases were placed in flasks (*J*). These were 300 cc. fractionating flasks with a stopcock at the outlet. As soon as the sample was placed in this flask, the stopcock was closed and a rubber stopper coated with the Khotinsky cement was sealed in at the mouth. The stopcocks on all the apparatus used in this were lubricated with a special mixture of 16 parts of vaseline, 1 part of paraffin, and 8 parts of pure rubber, maintained at a temperature of 350 to 400° for several hours.[1] The Putnam jars[2] were used for all samples from which the surrounding gas was to be removed by displacement. These were inverted and opened in a tank of water, saturated with CO_2 and illuminating gas, and all gas contained therein was removed by inserting a tube at the mouth and pulling the gas into a holder over mercury. The Mason jars were used for submerged samples. To remove the gas that adhered to the coal under water, the tops were removed and, as the gas was dislodged upon agitating the jars, it was collected in a bell jar, inverted over the top of the container.

V. EXPERIMENTAL DATA

The first set of experiments in connection with the study of the occluded gases in Illinois coal consisted of the examination of a vertical section from a pile of 1½ inch screenings that had been exposed outside for 5 months. At the time of collection, this pile had been smoldering for two months. Five days before taking the samples it had been wetted down. A core 7 in. in diameter and about 85 in. long was cut vertically from the pile by means of the cylindrical sampler. As the sampler went through the pile it was removed after going down 20 in., and the contents were, in each case, sampled separately. The samples were transferred at once to flasks, as shown by *J*, Fig. 1, and left in contact with the enclosed air for varying lengths of time as shown in the tables. The analyses of the different sections are given in Table VI.

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[1] Jour. Amer. Chem. Soc. Vol. 29, p. 1725.

[2] Univ. of Ill. Eng. Exp. Sta. Bull 17, p. 34.

TABLE VI

GASES IN COAL FROM SMOLDERING SCREENINGS

I Christian County screenings
First 20 inches of pile

II Christian County screenings
Second 20 inches of pile

III Christian County screenings
Third 20 inches of pile

IV Christian County screenings
Fourth 20 inches of pile

Part 1 Last Portion of Air

	I	II	III	IV
Time of Standing, days	2	1	1.	1
Weight of Coal, grams	200	200	200	200
Vol. of Gas at 0° C. 760 mm.	56.9	59.2	65.2	79.9
Cc. of Gas per 100 grams	28.45	29.6	32.6	38.95
CO_2	.7	.7	3.2	3.15
O	5.6	6.1	4.0	7.60
CH_4	.25	.05	0.	0.
N	21.90	22.75	25.4	28.20
Per cent by Volume				
CO_2	2.46	2.37	9.32	7.90
O	19.69	20.61	12.27	19.02
CH_4	.90	.17	0.	0.
N	76.95	76.85	78.41	73.08

Part 2 Gas Removed by Vacuum

Time of Standing, days	7	8	9	8
Weight of Coal, grams	200	200	200	200
Vol. of Gas at 0° C. 760 mm.	3.2	17.6	36.6	8.0
Cc. of Gas per 100 grams	1.6	8.8	18.3	4.0
CO_2	.5	2.2	4.05	1.85
O	0.	1.05	1.45	.45
CH_4	.1	.15	.75	.2
N	1.0	5.40	12.05	1.50
Per cent by Volume				
CO_2	31.25	25.0	22.13	46.25
O	0.	11.93	7.93	11.25
CH_4	6.25	1.70	4.10	5.00
N	62.50	61.37	65.84	37.50

TABLE VII

Composition of Gas Exuded from Fresh Coal

I Lebanon, Lebanon City Coal Co., sealed, dry.
II Lebanon, Lebanon City Coal Co., sealed, submerged.
III Bennett, Bennett Mine, International Coal Mining Co., sealed, dry.
IV Bennett, Bennett Mine, International Coal Mining Co., sealed, submerged.
V O'Fallon, Mine No. 2, St. Louis & O'Fallon Coal Co., sealed, dry.
VI O'Fallon, Mine No. 2, St. Louis & O'Fallon Coal Co., sealed, submerged.

	I	II	III	IV	V	VI
	Dry	Submerged	Dry	Submerged	Dry	Submerged
Weight of Coal, grams	642	800	648	800	787	800
Volume of Gas cc. (a)	446(b)	38.8	442(b)	29.3	331(b)	97.8
Per cent by Volume						
CO_2	0.	0.	5.88	0.	.88	0.
O	18.50	1.87	7.64	1.03	0.	1.08
CH_4	0.	55.97	0.	35.39	11.83	90.28
N	81.50	42.16	86.48	63.58	87.29	8.64

(a) At normal temperature and pressure.
(b) Total gas from containers.

In order to study the composition of the gas found in certain experiments[1] to be liberated from Illinois coal and shown also to be combustible, several samples were collected from fresh seam faces and allowed to stand for seven months. They were then opened under water and the gas surrounding the coal in the containers was collected by displacement. A similar set of samples was collected in jars which were filled with water and whatever gas had been given off at the end of seven months was collected. The results of these two sets of analyses are given in Table VII.

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[1] Jour. Am. Chem. Soc., Vol. 30, p. 1027.

It is evident that aside from the addition of methane and carbon dioxide to the ordinary constitutents of air, a decrease in the percentage of oxygen originally contained in the air of the jars has taken place. In order to test the extent of this absorption of oxygen, a number of samples of coal were placed in jars with large volumes of air equal to about six to ten times the several volumes of coal. After being in contact with the coal for a year the air was collected by displacement and analyzed. The following results show the general nature of the changes which had taken place, Table VIII.

TABLE VIII

The Absorption of Oxygen by Coal

I	Springfield, Sangamon Mine, Sangamon Coal Co.
II	Springfield, Sangamon Mine, Sangamon Coal Co.
III	Eldorado, Mine No. 8, O'Gara Coal Co.
IV	Marion, Chicago & Big Muddy Coal Co.
V	Herrin, Squirrel Ridge Mine, Chicago & Carterville Coal Co.
VI	DuQuoin, Greenwood, Davis Coal Co.
VII	Belleville, Suburban Coal Mining Co.
VIII	O'Fallon, Mine No. 2, St. Louis & O'Fallon Coal Co.

	I	II	III	IV	V	VI	VII	VIII
Weight of Coal in grams	109	139	180	183	146	134	138	153
Total Volume of Gas Enclosed in cc. at Normal Temperature and Pressure	873	849	816	814	843	853	850	837
Per cent by Volume								
CO_2	.48	.94	.68	1.87	.25	1.23	1.11	1.62
O	.16	.13	0.	0.	.25	0.	0.	1.45
CH_4	0.	0.	6.28	0.	2.17	0.	0.	0.
N	99.36	98.93	93.04	98.13	97.33	98.77	98.99	96.93

These two sets of analyses give some indication of the nature of the alterations that are going on when coal is exposed, but give no information as to the composition of the gas remaining in the coal. In addition, the samples were of various sizes of coal that had been broken from the face of the seam and they had been subjected to more or less exposure, even though but for short periods. In order to get coal closely representative of the material as it occurs in the seams, a set of samples of drill dust was collected in the following manner. As the drillings fell from the hole, they were collected in an ordinary half-liter fractionating flask fitted with a stopcock at the side tube. When the flask was filled it was sealed by a rubber stopper which was coated with the rubber resin vacuum cement. These flasks were taken to the laboratory as soon as possible, all the gases contained therein were removed by means of a mercury air pump and were collected over mercury. This portion of the gas is designated in the tables as *last air*. The flasks were then allowed to stand for several days after which they were again connected with the air pump and any gas that had been evolved was removed.

In order to have some extreme types of laboratory weathered samples to compare with the fresh drillings, a set of coals that had been used for some previous tests was evacuated in the above manner. These were portions of mine samples about two years old and had been quartered, reduced to buckwheat size, air-dried and enclosed in air-tight containers. These samples were transferred to flasks, as shown by *J* in Fig. 1, and evacuated by the mercury pump. The results are given in pairs, the fresh drillings being placed by the side of the samples two years in storage. These two series correspond as to location of the mines, so comparison of the changes in the occluded gases can be made by inspection of Table IX.

The striking feature of the above table is the large amount of combustible gases liberated by the fresh drillings. While this amounts to as much as 30 cc. per 100 grams, in the fresh samples, no such gases were detected in the old lots. However, it must be understood that the relative amounts of gas in coal from these various mines can not be critically judged from these analyses, as some of the working faces have been within short distances of long standing exposures[1]. Some idea of the rapidity of transpiration of occluded gases from exposed faces can be gathered from the following data.

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[1] A universal shutdown in the Illinois coal mines during April and a part of May, 1908, made it impossible to get samples representative of continuous workings.

As a drill hole was driven, the dust from the first 2½ feet was collected in one flask, while that from the last 3 feet was sealed in a separate container. As can be seen in Table X, the sample further from the exposed face contained more occluded gas and had less changes produced in what did remain.

TABLE IX

Comparison of Gases from Coals of Different Exposure Periods

I Springfield, Sangamon Mine, Sangamon Coal Co., fresh drillings.
II Springfield, Sangamon Mine, Sangamon Coal Co., face sample, 2 years old.
III Herrin, Squirrel Ridge Mine, Chicago & Carterville Coal Co., fresh drillings.
IV Herrin, Squirrel Ridge Mine, Chicago & Carterville Coal Co., face sample 2 years old.
V Clifford, Mine No. 8, Big Muddy Coal & Iron Co., fresh drillings.
VI Clifford, Mine No. 8, Big Muddy Coal & Iron Co., face sample 2 years old.
VII Marion, Mine No. 3, Peabody Coal Co., fresh drillings.
VIII Marion, Mine No. 3, Peabody Coal Co., face sample 2 years old.
IX Westville, Mine No. 44, Dering Coal Co., fresh drillings.
X Westville, Mine No. 44, Dering Coal Co., face sample 2 years old.

Part 1 Last Portion of Air

	I Fresh	II Old	III Fresh	IV Old	V Fresh	VI Old	VII Fresh	VIII Old	IX Fresh	X Old
Time of Standing, days	7	9	14	2	13	4	13	6	7	1
Weig't of Coal, grams	261	209	220	205	244	204	217	204	231	108
Volume of Gas cc. (*a*)	141.2	96.6	192.1	33.5	287.4	40.6	160.6	63.3	197.2	38.4
Cc. of Gas per 100 g. (*b*)	54.21	46.2	87.4	16.37	117.8	19.78	74.2	30.97	85.50	35.66
CO_2	2.12	1.91	3.37	1.27	6.65	1.23	3.27	.54	10.34	0.
O	2.87	2.06	.94	2.54	.58	2.75	.95	5.04	.95	7.90
CH_4	12.22	0.	18.70	0.	28.22	0.	1.57	0.	19.81	0.
N	37.00	42.23	64.05	12.56	72.40	15.81	68.20	25.39	54.40	27.76
Per cent by Volume										
CO_2	3.92	4.15	3.86	7.80	5.56	6.80	4.43	1.79	0.	12.09
O	5.30	4.46	1.04	15.50	.49	13.80	1.28	16.25	22.20	1.11
CH_4	22.53	0.	21.79	0.	32.44	0.	2.12	0.	0.	23.17
N	68.65	91.39	73.31	76.70	61.51	79.4	92.17	81.96	77.80	63.63

Part 2 Gas Removed by Vacuum

	I Fresh	II Old	III Fresh	IV Old	V Fresh	VI Old	VII Fresh	VIII Old	IX Fresh	X Old
Time of Standing, days	13	8	12	10	13	12	13	11	13	10
Weig't of Coal, grams	261	209	220	205	244	204	217	204	231	108
Volume of Gas cc. (*a*)	26.9	14.9	48.8	1.9	76.4	5.8	20.4	20.5	26.0	1.1
Cc. of Gas per 100 g. (*b*)	10.31	7.12	22.18	1.08	31.30	2.84	9.4	10.04	11.26	1.02
CO_2	1.84	2.74	1.68	....	4.63	.69	3.18	2.01	3.51	.56
O	.50	.10	.14	....	.29	.15	0.	0.	.82	.10
CH_4	6.14	0.	19.21	....	22.20	0.	.09	0.	2.17	0.
N	1.83	1.27	1.21	....	4.18	1.88	6.13	8.03	4.76	.36
Per cent by Volume										
CO_2	17.85	80.50	7.58	....	14.79	24.20	33.84	20.0	32.09	54.60
O	4.83	1.30	.61	....	.92	5.90	0.	0.	7.32	9.90
CH_4	59.59	0.	86.37	....	70.93	0.	1.00	0.	19.26	0.
N	17.73	18.20	5.44	....	13.36	69.90	65.16	80.0	41.33	35.50

(*a*) At 0° C and 760 mm. pressure. (*b*) Figured to coal as sampled.

TABLE X

Gases from Coal Drillings Taken at Varying Distances from the Face Opening

I Westville, drillings from first 2½ feet of hole, last air.
II " " " last 3 " " " " "
III " " " first 2½ " " " gas by vacuum.
IV " " " last 3 " " " " " "

	I	II	III	IV
Time of Standing, days	7	7	13	13
Weight of Coal	182	231	182	231
Volume of Gas at 0° C. 760 mm.	174	197.2	9.6	26.0
Cc. of Gas per 100 g. of coal	95.60	85.50	5.27	11.26
CO_2	7.23	10.34	1.76	3.51
O	.59	.95	0.	.82
CH_4	11.29	19.81	2.30	2.17
N	76.40	54.40	1.21	4.76
Per cent by Volume				
CO_2	7.57	12.09	33.33	32.09
O	.62	1.11	0.	7.32
CH_4	11.73	23.17	43.74	19.26
N	80.08	63.63	22.93	41.33

In addition to the loss of combustible gases, the fresh samples of drillings showed more extensive absorption than did the laboratory weathered ones. From this it may be concluded either that the oxygen has entered into some combination with the coal itself, or that a reaction has taken place, resulting in the formation of carbon dioxide. The presence of considerable amounts of carbon dioxide in the gases from the fresh samples seems to bear out the latter conclusion, although it does not completely replace the oxygen of the air. It may also be possible that the carbon dioxide formed and taking the place of the occluded gases is only given off at higher temperatures. That this is true to some extent is shown by the fact that 69% of the gases removed from one of these fresh samples at 100°C. consisted of carbon dioxide. This phase of the matter is receiving furthur study.

It is certainly true that this absorption of oxygen takes place either contemporaneously or as soon as the gases escape from the fresh coal. A study of some of the stages of this absorption or oxidation can be made from Table XI.

TABLE XI

AVIDITY OF OLD AND FRESH COAL FOR OXYGEN

I Atmosphere surrounding old face sample in contact with large volume of air for 2 years.
II Old face sample sealed in fresh air 2 days, then evacuated.
III Drillings, sealed 14 days.
IV " in vacuum 12 days.
V " second air in contact with coal 7 days.

	I	II	III	IV	V
Weight of Coal, grams	146	205.5	220	220	220
Volume of Gas, cc.	843	33.5	192.1	48.8	130.4
Per cent by Volume					
CO_2	.25	7.80	3.86	7.58	1.63
O	.25	15.50	1.04	.61	.37
CH_4	2.17	0.	21.79	86.37	14.14
N	97.33	76.70	73.31	5.44	83.86

In this table all samples were from the same mine. No. I and II were partially air-dried face samples, which had been sealed in Putnam jars for some two years. From No. I the surrounding air in the container was collected by displacement and analyzed.

No. II was left in one of the sealed fractionating flasks for two days. At the end of that time both the surrounding air and some of the enclosed gases were removed by means of the air pump. No. III is a flask of fresh drillings from which the surrounding air and occluded gases were removed by vacuum, as above. No. IV is the analysis of the further gas given off after the surrounding air had been removed and the flask had stood in a vacuum for twelve days. No. V is the analysis of the air that had been readmitted to the evacuated flask and left in contact with the coal for seven days.

Further comparison of the rapidity of oxidation can be made from Table XII. All samples were from the same mine. No. I and II had been in laboratory containers for over two years. Two portions were transferred to the flasks and left in contact with normal air for two and six days respectively.

TABLE XII

RAPIDITY OF OXIDATION IN FRESH AND OLD SAMPLES OF COAL

I Old face sample sealed 2 days, last air.
II " " " second air in contact 6 days.
III Fresh drillings, sealed 14 days, last air.
IV Drillings, second air in contact 7 days.
V Fresh drillings, sealed 13 days, last air.
VI Drillings, second air in contact 8 days.

	I	II	III	IV	V	VI
Weight of Coal, grams	204	204	220	220	244	244
Volume of Gas at 0°C & 760 mm.	40.6	253.1	192.	130.4	287	157.
Cc. per 100 g. of Coal	19.78	124.2	87.40	59.28	117.7	64.4
CO_2	1.23	1.95	3.37	.97	6.65	2.02
O	2.75	7.24	.94	.22	.58	.15
CH_4	0.	0.	19.04	8.38	13.14	8.84
N	15.81	115.0	64.05	49.71	97.0	53.39
Per cent by Volume						
CO_2	6.80	1.57	3.86	1.63	5.56	3.14
O	13.80	5.83	1.04	.37	.49	.23
CH_4	0.	0.	21.79	14.14	11.14	13.70
N	79.40	92.60	73.39	83.86	82.81	82.93

The preceding results have thrown some light upon the changes produced by the deterioration of sealed laboratory samples but contain no data on samples subjected to outside exposure. Table XIII gives a comparison between samples of fresh

TABLE XIII

COMPARISON OF ACTIVITY AS BETWEEN SEALED AND EXPOSED SAMPLES OF COAL

I Westville, Mine No. 44, Dering Coal Co., fresh drillings, sealed.
II “ “ “ “ “ “ “ exposed screenings, 15 mo. old.
III “ “ “ “ “ “ “ “ “ 2 “ “
IV Marion, Mine No. 3, Peabody Coal Co., fresh drillings.
V “ Binkley, Miles Coal Co., outcrop coal.
VI Springfield, Sangamon Mine, Sangamon Coal Co., fresh drillings.
VII “ “ “ “ “ “ screenings, 2 mo. old.

Part 1 Last Portion of Air

	I Fresh	II Exposed	III Exposed	IV Fresh	V Exposed	VI Fresh	VII Exposed
Time of Standing, days	7	3	6	13	19	7	3
Weight of Coal, grams	231	200	200	217	224	261	200
Volume of Gas, 0°C. 760 mm.	197.2	44.2	55.8	160.6	134.3	141.2	240.5
Cc of Gas per 100 g.	85.50	22.10	27.9	74.2	60.0	54.21	120.3
CO_2	10.34	1.40	.25	3.27	3.38	2.12	3.03
O	.95	3.25	5.75	.95	.38	2.87	22.09
CH_4	19.81	0.	0.	1.57	.54	12.22	.66
N	54.40	17.45	21.90	68.20	55.70	37.00	94.47
Per cent by Volume							
CO_2	12.09	6.34	.90	4.43	5.64	3.92	2.51
O	1.11	14.71	20.61	1.28	.64	5.30	18.36
CH_4	23.17	0.	0.	2.12	.54	22.53	.55
N	63.63	78.95	78.49	92.17	93.18	68.65	78.58

Part 2 Gas Removed by Vacuum

	I Fresh	II Exposed	III Exposed	IV Fresh	V Exposed	VI Fresh	VII Exposed
Time of Standing, days	13	14	13	13	7	13	13
Weight of Coal, grams	231	200	200	217	217	261	200
Volume of Gas, 0°C. 760 mm.	26.0	26.9	16.8	20.4	19.9	26.9	23.9
Cc of Gas per 100 g.	11.26	13.45	8.4	9.40	8.88	10.31	11.95
CO_2	3.51	1.4	2.85	3.18	2.99	1.84	2.39
O	.82	2.8	.7	0.	.36	.50	.81
CH_4	2.17	.15	.6	.09	.10	6.14	2.39
N	4.76	9.10	4.25	6.13	5.43	1.83	6.36
Per cent by Volume							
CO_2	32.09	10.41	33.93	33.84	33.67	17.85	20.00
O	7.32	20.82	8.33	0.	4.02	4.83	6.78
CH_4	19.26	1.12	7.15	1.00	1.05	59.59	20.00
N	41.33	67.65	50.59	65.16	61.26	17.73	53.22

drillings and samples exposed to the weather. No. I is a sample of fresh drillings from Westville, while No. II was collected from the surface of a pile of 1½ inch screenings from the same mine and had been stored outside for fifteen months. No. III is from the surface of a pile of the same screenings that had been stored outside for two months. No. IV is a sample of fresh drillings from Marion, while No. V is from an outcrop of the same seam one mile from the place where No. IV was taken. This outcrop had been exposed for one year. No. VI is a sample of drillings from Springfield, while No. VII was collected from the surface of a pile of 1½ inch screenings from the same mine. These screenings had been stored outside for two months. Samples of each type were sealed in the evacuating flasks, *J*, of Fig. 1, together with normal air for periods of from three to nineteen days, indicated in the following table. Upon applying the vacuum, the first portion of air, to about 150 mm. pressure, was discarded. The last portion secured by carrying the vacuum to the limit gives essentially the composition of the gases contained in the coal proper, as shown in Table XIII, Part 1. Without the readmission of air the flasks were set aside for varying periods and a second application of the vacuum gave results as shown in Part 2.

VI SUMMARY

It seems evident from a study of the results presented in the foregoing pages, that two active processes are set up immediately upon the liberation of coal from the vein. The first is an exudation of hydrocarbons, mainly consisting of marsh gas (CH_4); the second is an absorption of oxygen. There can be little question, moreover, that these alterations proceed simultaneously. In Tables IX and X, for example, on pages 21 and 22, there are present in the gases from all the samples of fresh drillings, notable quantities of methane, ranging from 18% to 86% of the various gas volumes. At the same time the oxygen present has dropped down in a very positive manner, in some cases even reaching the vanishing point. That this transpiration of gases is interdependent and is of the nature of an osmotic exchange can hardly be affirmed as an explanation of the phenomenon. On the contrary, there seems to be evidence that the gases operate independently of each other. Take for example the figures for marsh gas. In the case of the samples listed in Table IX, the exudation of CH_4 seems to have spent itself in those samples held in laboratory containers for two years. In no case is there evidence of further liberation of this gas, even with thorough application of the vacuum. Table XI shows a similar condition, in that an evacuation of the gases from the two year old sample, as in No. II, shows no marsh gas present. Similar results are seen in samples No. I and II in Table XII. In Table XIII the completion of this exudation would seem to be reached after two months, though it is well to note that by forcing, as with a vacuum in the second part of this table, the two months old samples may be made to yield more methane, though in relatively small quantities.

On the other hand, the avidity of the coal for oxygen seems to be pronounced at the very beginning of the exposure of the freshly mined material, and while there are a number of cases where a certain agreement seems to exist between the in-going and the out going marsh gas, still there are more cases where the absorption of oxygen is pronounced without any evidence of marsh gas being present. For example, attention may be called especially to samples No. II, IV, VI, and VIII, in Table IX. In all of these cases the oxygen-nitrogen ratio shows a positive diminution of the oxygen from the normal ratio of approximately 1:4 with practically no evidence of marsh gas being present. While the statement, therefore, may be modified by further study, it seems fair to conclude, for the present, that there is no necessary connection, at least of a strictly chemical nature, between the exudation of marsh gas and the absorption of oxygen.

Again, the liberation of CH_4, while very active in the first few days after removal of the coal from the ground, diminishes in amount quite rapidly till, after the second month, there is very little of this gas in evidence. The activity of the coal for oxygen, on the contrary, seems to be of longer duration. In Table XII, samples No. I and II were collected June 1, 1906. The tests for the table were made in May and June, 1908. There is marked absorption of oxygen in sample No. I after two days' exposure in the flask to normal air, while No. II, with five days' exposure, shows still further reduction in the oxygen ratio without accompanying evidence, also, it should be noted, of marsh gas. Similarly, samples No. II, IV, VI, and VIII, of Table IX, show a marked avidity for oxygen after two years from time of collecting.

These facts have a direct bearing on the topic of deterioration, as substantially defining the limit as to time of that form of alteration. While varying somewhat in different coals, the loss of hydrocarbons for the most part is practically complete at the end of two months. These facts have a bearing also upon the matter of weathering, and indirectly upon the matter of spontaneous combustion. The absorption of oxygen is undoubtedly closely associated with both of these phenomena. Our studies upon the weathering processes coincide with these studies in gases, namely, that in all probability this low type of oxidation extends over an indefinite length of time. Moreover, while under normal conditions there is effected but a very slight oxidation and loss of fuel values, the conditions are favorable, as, for example, upon an increase of temperature, for bringing about a very rapid combination with oxygen even to the point of combustion.

How far this absorption of oxygen is a chemical reaction, or low combustion resulting in CO_2 and H_2O, and how far it is an absorption into the molecular structure and composition of the coal must be left for further study.

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

(To April 1, 1909)

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print.*)

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905. (*Out of print.*)

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. (*Out of print.*)

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906. (*Out of print.*)

Circular No. 3. Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907, by L. P. Breckenridge. 1909.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (*Out of print.*)

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UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 33 MARCH 1909

TESTS OF TUNGSTEN LAMPS

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I. INTRODUCTION

When the tungsten incandescent lamp was put on the market, about a year and a half ago, its high efficiency and excellent quality of light were in a large measure offset by the extreme fragility of its filament, its uncertain life and its high price. For instance, in October, 1907, when German tungsten lamps were just being introduced into this country, the Engineering Experiment Station bought a dozen of the 40-watt size (the smallest obtainable at that time) for testing purposes, at a cost of $1.50 each. They came by express, packed with as much care and skill as was thought necessary, but when the lamps were received only five of the twelve had unbroken filaments, and these five had an average life of 50 or 75 hours only. This experience was a typical one with tungsten lamps at that time.

Since then many companies have entered the field of tungsten lamp manufacture, and they have all striven to overcome the faults common to those early lamps. In their attempts to make a lamp that would better withstand shipment and handling, that would not blacken and burn out early in its life and that could be burned in other than the vertical pendant position necessary with the first lamps, the manufacturers have developed several types of tungsten lamps. These differ considerably in two respects: (1) the method of manufacture; and (2) the scheme of mounting the filaments.

This bulletin describes a study of three prominent types of tungsten lamps, differing considerably in the above respects. This study was made with the idea of bringing out, as far as possible, the good as well as the poor points in the construction and manufacture of each type. There are included the results of tests showing what may be expected of the present day low wattage tungsten lamps in the way of life, maintenance of candle power and efficiency under different operating conditions.

II. Description of Lamps

Of the lamps chosen for the tests, one type was of American and two were of German manufacture. They will be designated as the *P, D* and *C* lamps, respectively. They represented three of the principal processes used in the manufacture, and three common schemes of mounting tungsten lamp filaments at the time the tests were started. All lamps tested were chosen from a lot of 100 of each type of lamp.

Rating.—All three lamps were rated at 25 watts at 110 volts and advertised to give an efficiency of 1.25 watts per candle-power. Fig. 1, 2 and 3 show the candle-power and watt per candle values for the individual lamps when new, and the average curve drawn through these points for the 100 lamps of each kind. It will be seen from the curves that the average watt per candle efficiency of the *C* lamps is somewhat poorer than the others. This can perhaps be explained by the fact that its filament is supported by three times as many spires as the other two, and hence more of

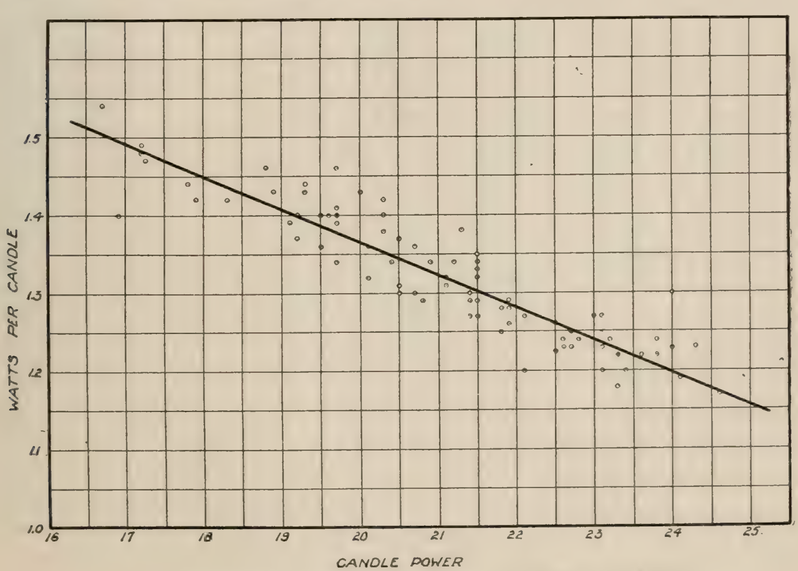

DIAGRAM SHOWING RATINGS OF 100 C LAMPS.

Fig. 1

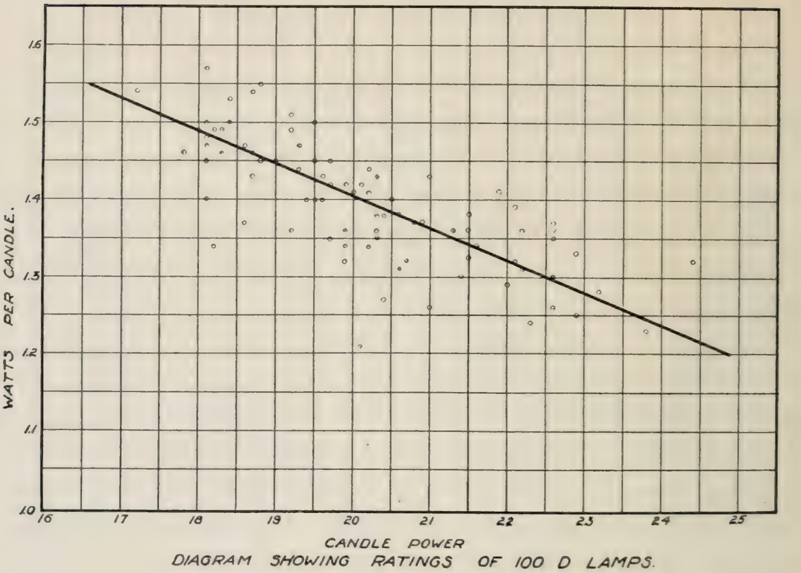
WATTS PER CANDLE.
1.6
1.5
1.4
1.3
1.2
1.1
1.0
16
17
18
19
20
21
22
23
24
25
CANDLE POWER
DIAGRAM SHOWING RATINGS OF 100 D LAMPS.

FIG. 2

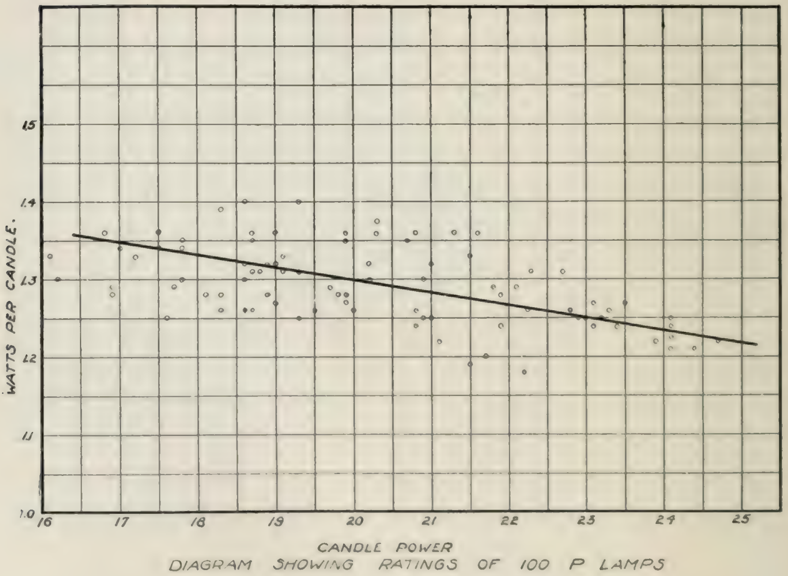
WATTS PER CANDLE.
1.5
1.4
1.3
1.2
1.1
1.0
16
17
18
19
20
21
22
23
24
25
CANDLE POWER
DIAGRAM SHOWING RATINGS OF 100 P LAMPS

FIG. 3

the filament is kept cooled below incandescence. In the *D* and *P* lamps, each one of the tip end spires cools approximately 1/8 inch of filament, so that it produces little or no light, while the spires at the base end each cool approximately 1/16 inch. This makes about one inch of filament in each lamp that acts merely as a resistance. In the *C* lamp there are 16 spires, each cooling a short length, so that there are about 2 1-2 inches of ineffective filament so far as light production is concerned. This would account for the difference in efficiency between this lamp and the other two, since the main part of the filaments is operated at approximately the same temperature.

Filaments.—The filaments of the American lamp (*P*) were manufactured by the paste or Auer process. In this method, which is similar to the one used in making ordinary carbon filaments, finely powdered tungsten is mixed with a suitable binder, such as sugar or some other organic substance, and the resulting paste is squirted through a diamond die under great pressure. The moist filament so formed is then heated in an atmosphere of steam and hydrogen to remove the carbon of the binding material. This leaves a filament of almost pure tungsten. The filament, as mounted in the lamp, consists of four hairpin loops connected in series and mounted upon supporting spires. Connections between the loops are made at the base end of the stem by fusing together the filaments and the spires. The filaments are hung loosely on the spires so as to allow for the contraction that takes place after they have been burned for a time.

The filament of the first German lamp (*D*) is made by the deposition process. In this method a fine filament of carbon is heated in an atmosphere of some compound of tungsten, for instance, oxychloride of tungsten. This causes the metal to be deposited in a shell upon the carbon core. By the application of heat the tungsten and carbon are made to unite chemically to form tungsten carbide, which is then reduced and the carbon removed by a method similar to that employed in the paste process. The filament in this lamp also consists of four loops, but the supporting spires at the tip end of the stem are very thin and flexible springs, and the filament is kept under a slight tension by their action. The flexibility of these spires also permits contraction of the filaments to take place. The entire glass stem which carries the filaments is mounted between two coil springs, as shown in Fig. 4. The object of these springs is to absorb the jar and vibration to which the lamp may be subjected and so prevent breaking the filament. Connections between the filament and spires at the base end of the stem are made by means of pasted joints.

The second German lamp (*C*) is made by the colloid process. In this method colloidal tungsten is formed either by maintaining an arc between tungsten electrodes under some liquid, it may be water, or by reducing tungstic trioxide with potassium cyanide. This plastic colloidal mass is brought to the proper consistency, and is then squirted through a die to form a filament, as in the paste process. The filament so obtained is dried and is gradually brought to a white heat in a nonoxidizing atmosphere, and is thereby converted into the crystalline state. The filament in this lamp, too, consists of four loops, each of which is mounted in a peculiar spiral shape and hung loosely enough to permit of contraction. The joints between the filaments and the base spires are fused as in the *P* lamp.

TABLE 1

DIMENSIONS OF FILAMENTS

Lamp	Total Length inches	Diameter inches	Total Area of Surface square inches
C	19.87	.00138	.0859
D	15.92	.00202	.1009
P	19.27	.00163	.0987

The shapes of the bulbs and their comparative sizes are shown in Fig 4. The bulb of the *P* lamp is identical with that on the ordinary 16 candle-power carbon lamps in use in this country.

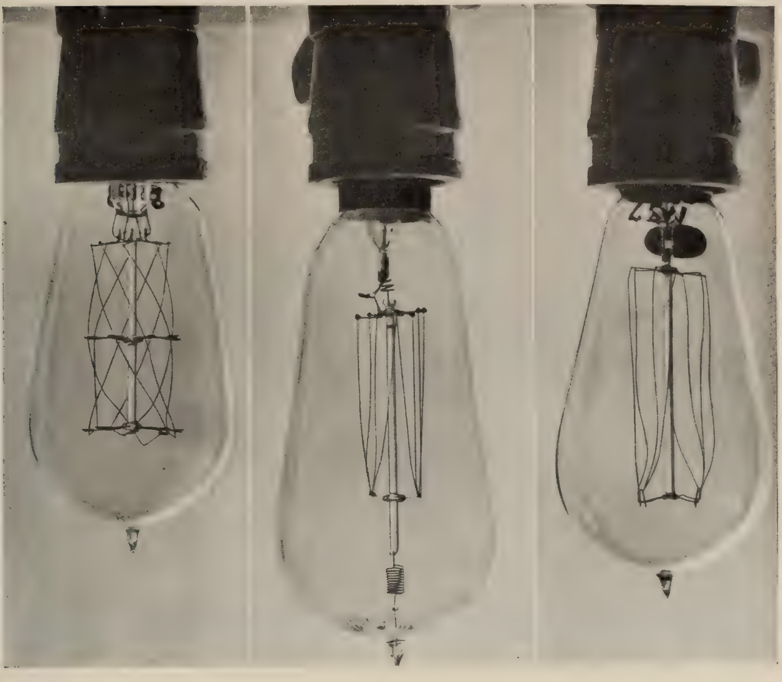

FIG. 4

III. ELECTRICAL CHARACTERISTICS[1]

All three filaments, being of metal, have of course a positive temperature coefficient. Fig. 5 shows the temperature resistance curves for one lamp, selected at random from each of the three lots of lamps received. Fig. 6 is a curve between current and resistance that is typical of all three lamps.

As is the case with all lamps having filaments with a large positive temperature coefficient, the current, when first turned on, has a value several times greater than the normal operating value. Fig. 7 is a curve taken by means of an oscillograph, showing this change of current from the instant of starting. The very low re-

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[1] In some of the curve sheets that follow, curves for only one kind of lamp are given. In these cases the results for all lamps are practically the same.

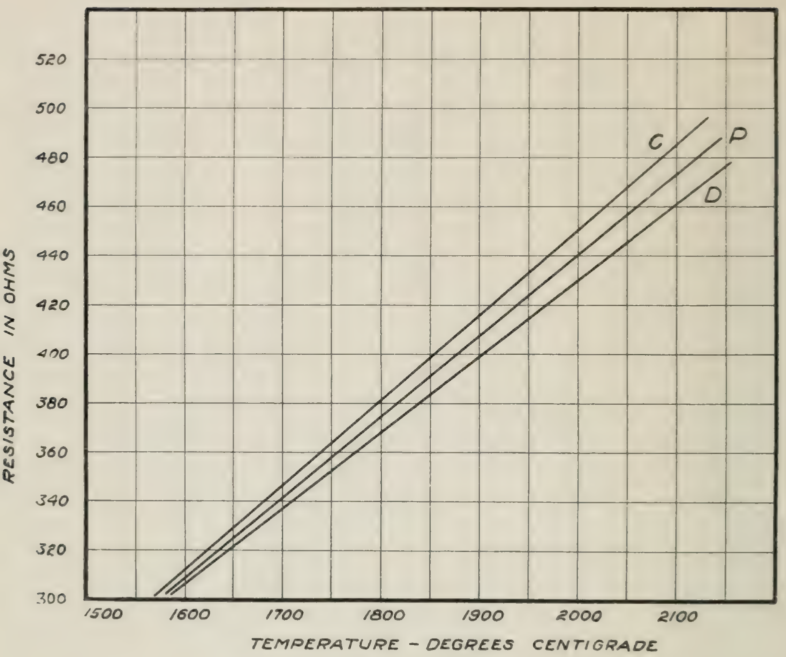

520
500
480
460
440
420
400
380
360
340
320
300
RESISTANCE IN OHMS
1500
1600
1700
1800
1900
2000
2100
TEMPERATURE - DEGREES CENTIGRADE
C
P
D

FIG. 5

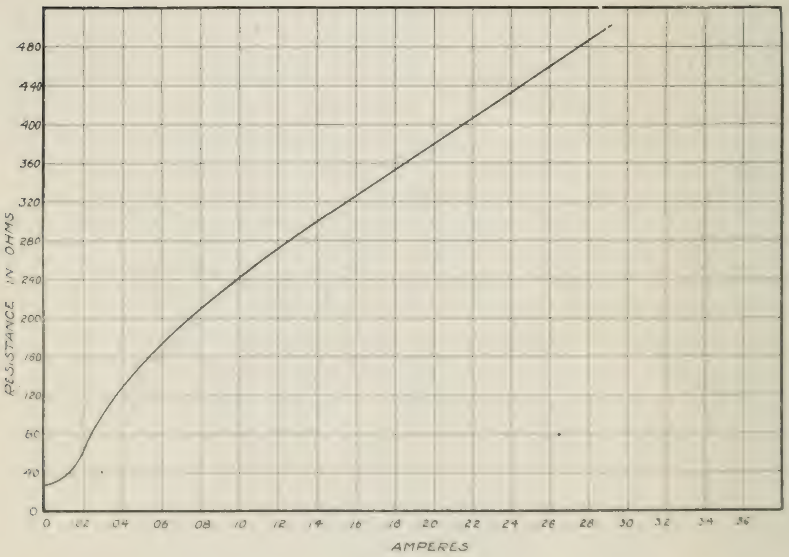
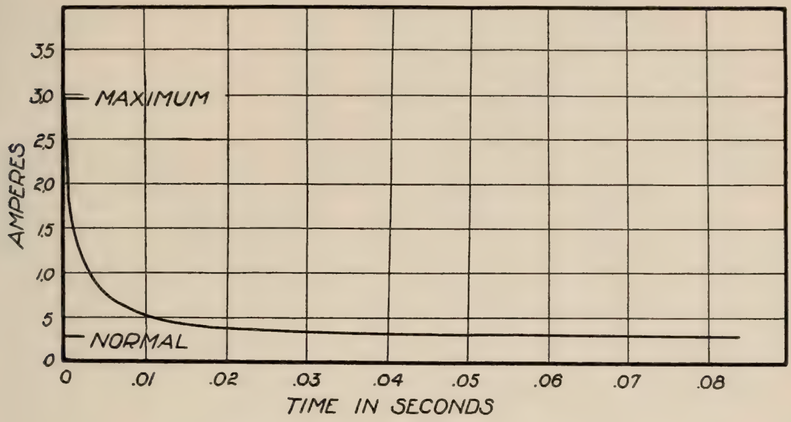

480
440
400
360
320
280
240
200
160
120
80
40
0
RESISTANCE IN OHMS
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30
.32
.34
.36
AMPERES

FIG. 6

sistance when the filament is cold, i. e., at zero current, as shown in Fig. 6, gives rise to a heavy rush of current at the first instant which quickly decreases, owing to the rapid increase of resistance as the filament heats up. This current rush, when the lamp is turned on, causes the familiar flash or sudden rise in candle-power above normal, commonly known as overshooting.



STARTING CURRENT CURVE.

FIG. 7

The curves between candle-power and voltage, and between watts per candle and voltage, are shown in Fig. 8. The equation for the former, obtained by the method of least squares is

$$CP = 213.7 \times 10^{-8} \times E^{3.44}$$

Fig. 9 shows curves plotted between watts per candle and temperature,[1] for one lamp of each kind. These curves lie very close together, indicating that throughout the temperature range all three filaments give approximately equal watt per candle efficiencies for the same filament temperatures. Fig. 10 gives curves between temperature and spherical candle power per square inch of total filament area or emissivity. These indicate that the C lamp has the highest and the D lamp the lowest emissivity at all temperatures. This can be explained by an examination of the fila-

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[1] The temperatures given in this bulletin are black body temperatures and are given as relative rather than absolute values.

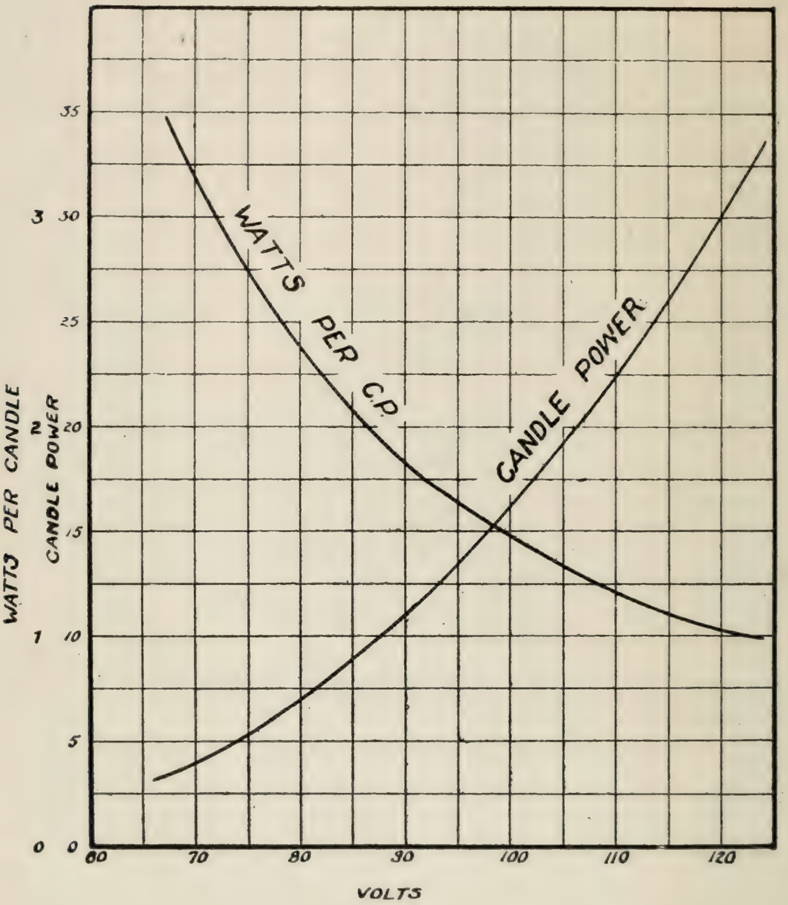


Fig. 8

ments under a microscope. Fig. 11 is a sketch of all three filaments showing their appearance when magnified. The *C* filament is seen to be the smoothest one of the three. It has no pits or protuberances, but has a smooth shiny surface broken only by what look like fine cracks similar to the fine check cracks sometimes seen in the glazes of porcelains. Such a smooth polished surface would naturally have a high emissivity. The *P* filament seems smooth, i. e., is free from knobs and protuberances, though it is covered with small depressions and wrinkles, probably due to the

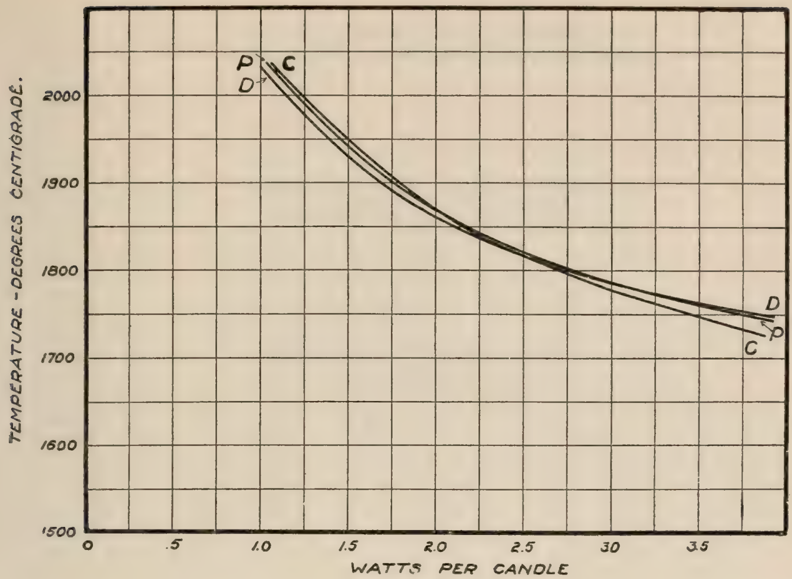

P
C
D
D
P
C
2000
1900
1800
1700
1600
1500
TEMPERATURE - DEGREES CENTIGRADE.
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
WATTS PER CANDLE

FIG. 9

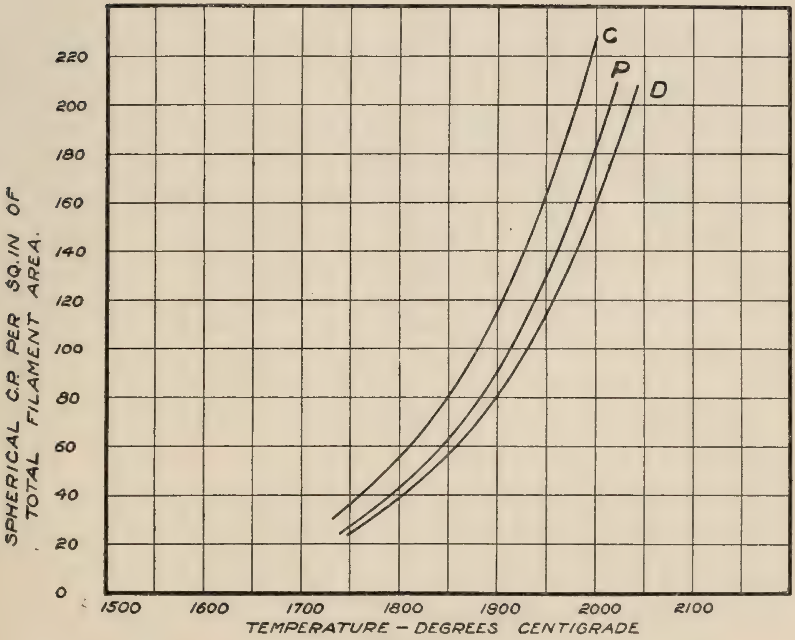
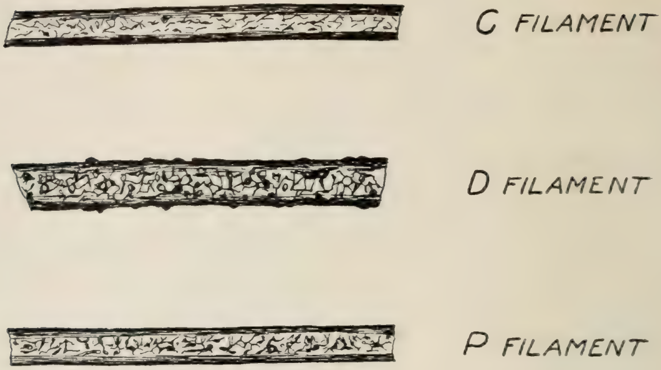

C
P
D
220
200
180
160
140
120
100
80
60
40
20
0
SPHERICAL C.P. PER SQ.IN OF TOTAL FILAMENT AREA.
1500
1600
1700
1800
1900
2000
2100
TEMPERATURE - DEGREES CENTIGRADE

FIG. 10



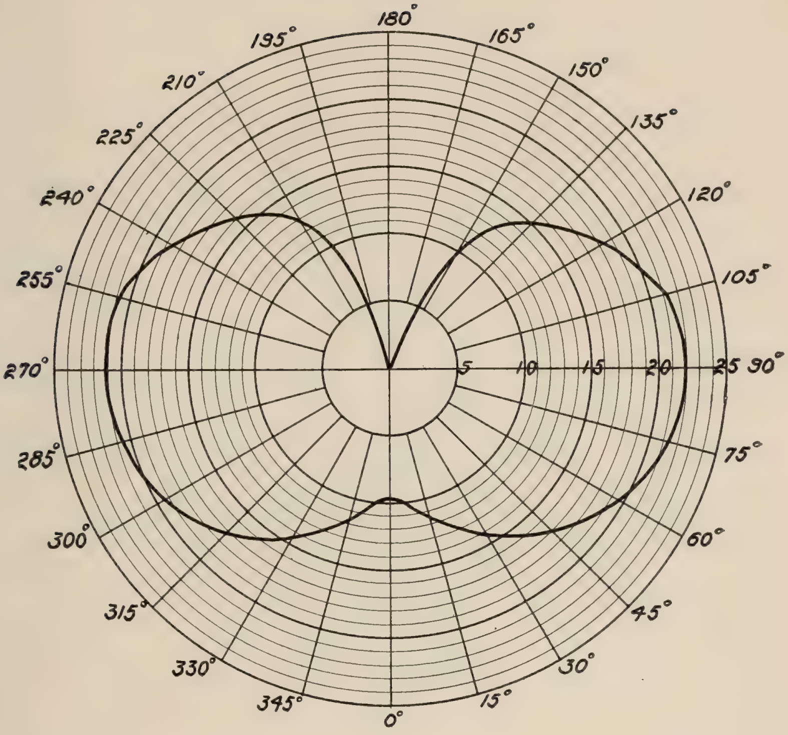
SKETCH OF NEW FILAMENTS WHEN MAGNIFIED.

Fig. 11

removal of the carbon of the binder and the consequent shrinkage. The lines shown on the filament in the sketch represent fine wrinkles rather than cracks on the surface of the filament. These depressions and wrinkles on the surface make its emissivity somewhat less than that of the smoother *C* filament. The *D* filament is the roughest and most uneven of the three. It is covered with many knobs and protuberances, pits and large wrinkles. This rough surface naturally has a lower emissivity than the other two lamps.

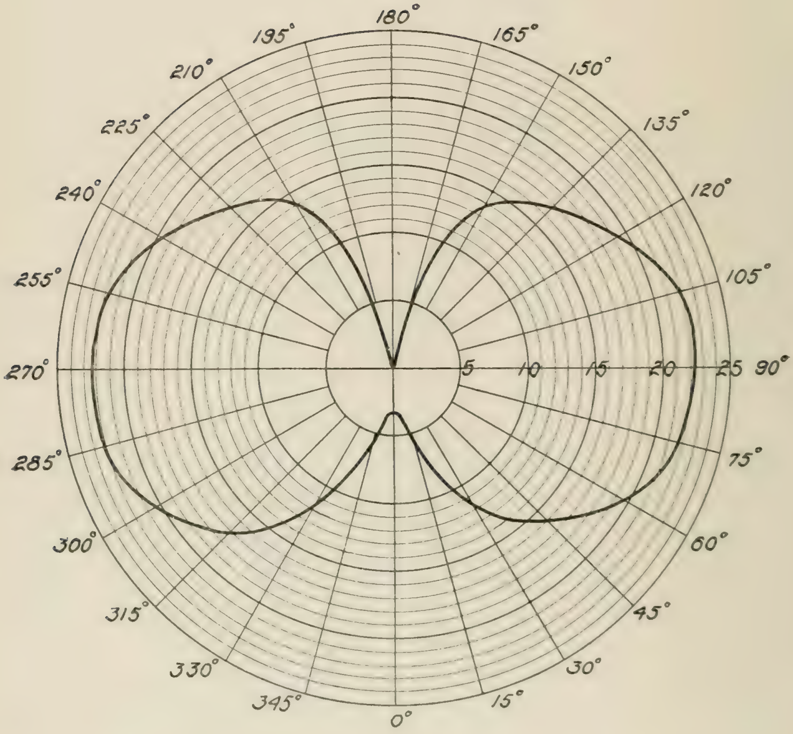
IV. Distribution

The horizontal distribution curves for all three lamps are approximately circles, as would be expected from the number and arrangement of the filaments. The vertical distribution curves are shown in Fig. 12, 13 and 14. The *D* lamp has the lowest tip candle power, the *P* lamp next, and the *C* lamp the highest,—nearly 10



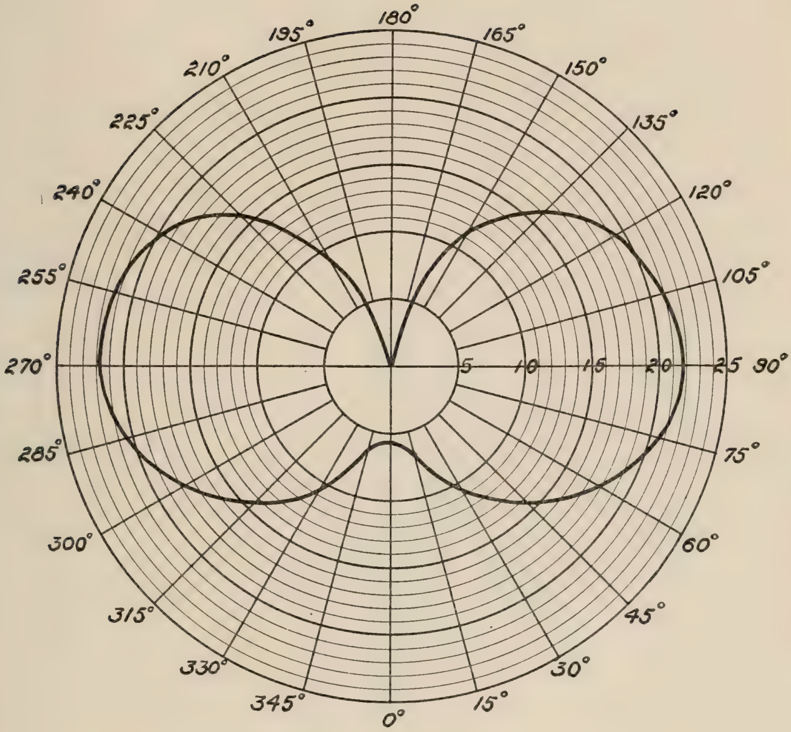
VERTICAL DISTRIBUTION OF [illegible]C LAMP

FIG. 12



VERTICAL DISTRIBUTION OF D LAMP

FIG. 13



VERTICAL DISTRIBUTION OF P LAMP

FIG. 14

candle-power. The spherical reduction factors for the lamps are shown in the following table.

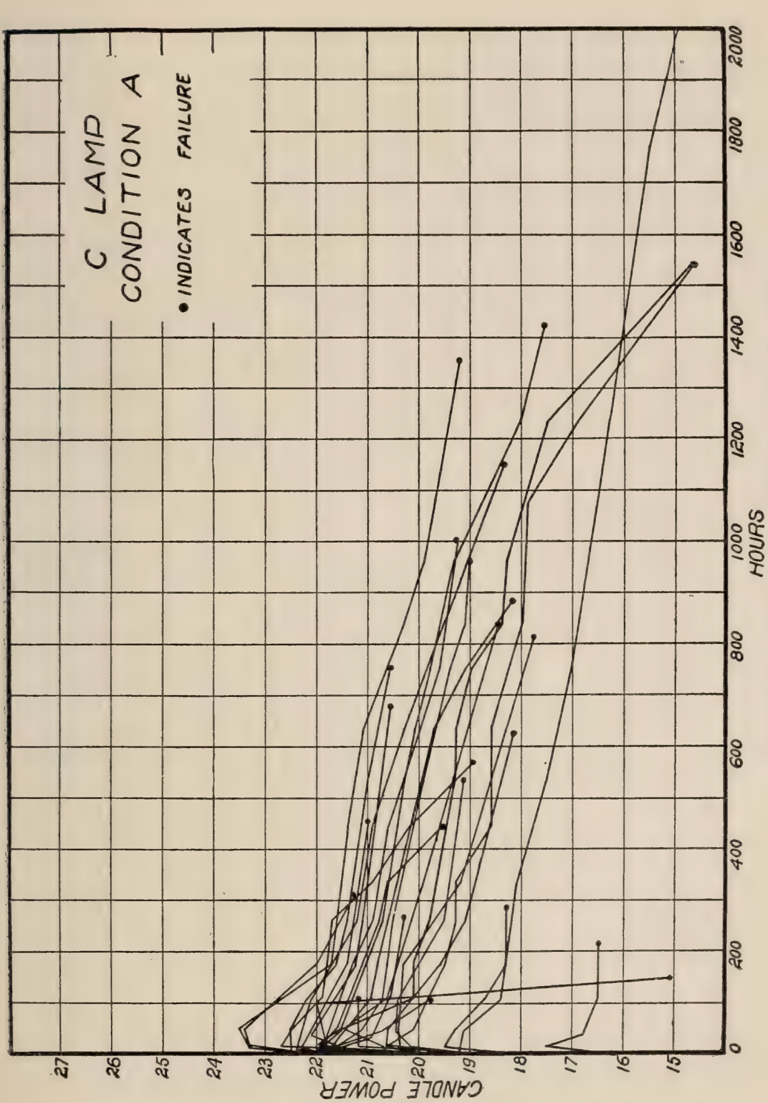
TABLE 2

Lamp	Mean Horizontal Candle Power	Mean Spherical Candle Power	Spherical Reduction Factor
C	21.1	17.7	.840
D	22.2	16.2	.730
P	21.9	17.2	.785

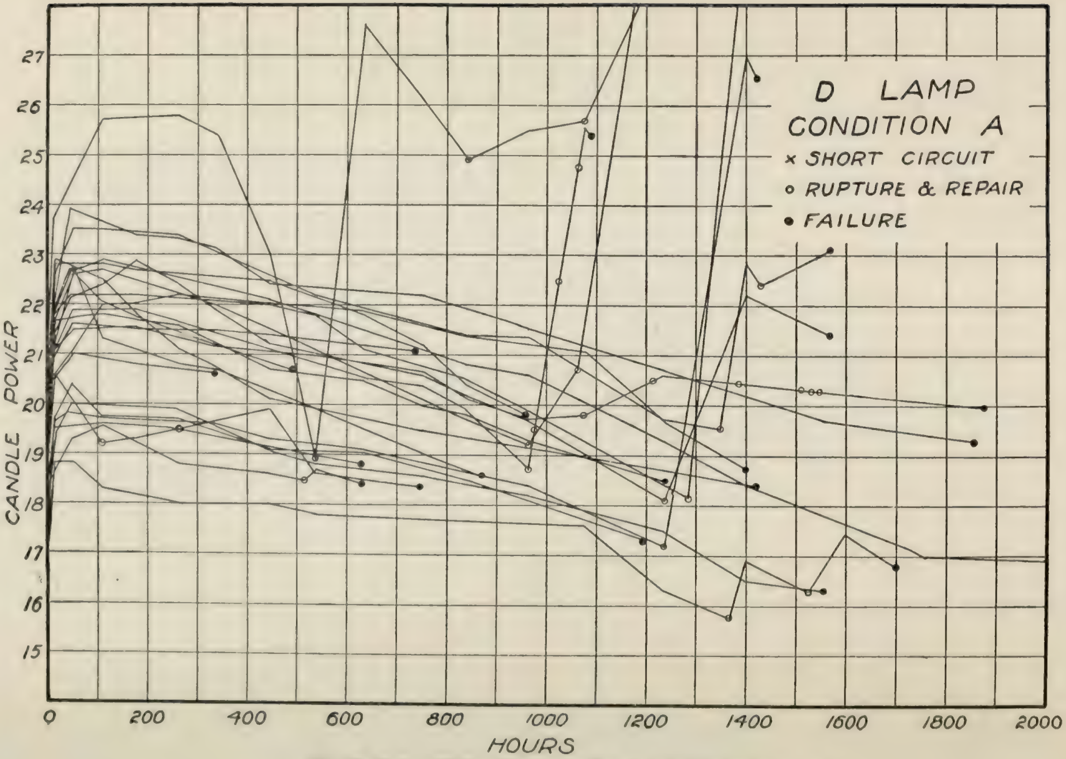
V. LIFE TESTS

For the life tests, 50 lamps of each kind were selected. Of these, 25 of each kind were burned upon a well-regulated voltage, supplied by a storage battery floating across constant voltage mains. The racks holding the lamps were supported by three coil springs in order to protect them from the vibration of the building. This condition will be designated as A, and represents exceedingly good operating conditions. The remaining 25 lamps of each kind were operated upon 60-cycle alternating current mains having a badly fluctuating voltage. The rack supporting these lamps was rigidly fastened to the floor and received all of the vibration of the building. This vibration was caused by the engines of the University power plant and the machines in the electrical laboratory two floors below. It was great enough to be easily felt by placing the hand on the rack, and the lamps themselves could be seen to vibrate. It was not so severe a vibration as that to which lamps would be subjected in many manufacturing plants, but it was severe enough to represent rather trying operating conditions. This condition will be designated as condition B. Fig. 15 to 20 show the candle-power performance of each lamp on the life tests for both operating conditions.

In the life test under condition A, readings were taken up to 2000 hours. At the end of this time there was one *C* lamp, one *D* lamp and thirteen *P* lamps still burning. The method of mounting the filament of the *C* lamp is such that it is seldom that a brok-

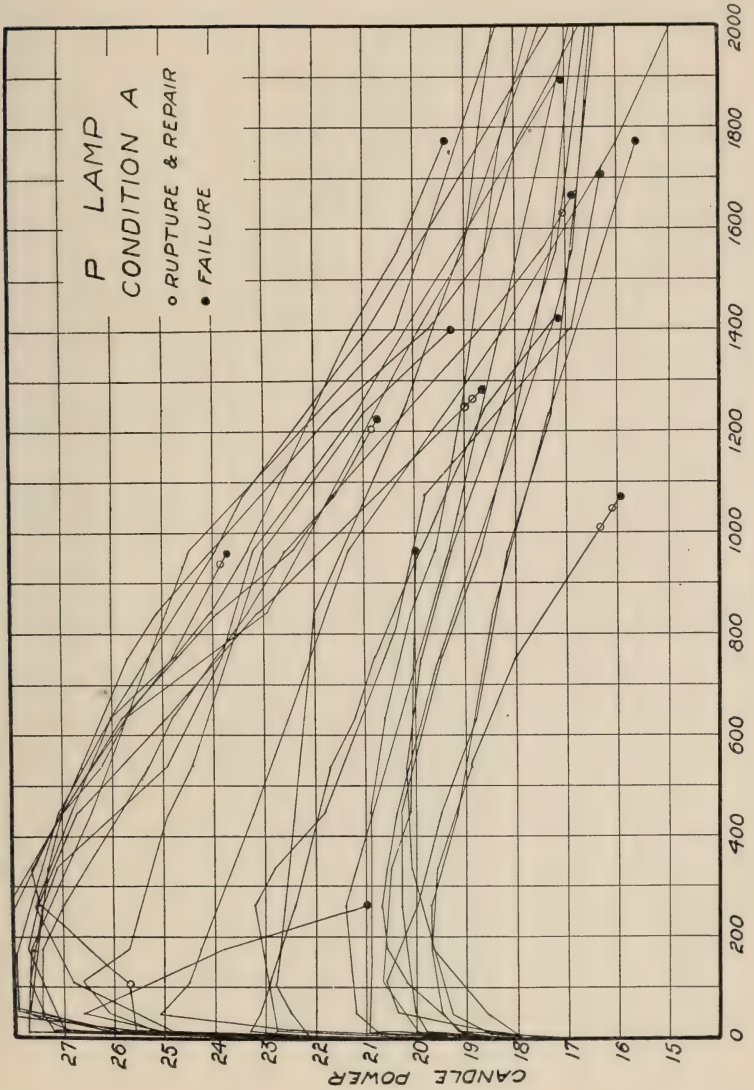


CURVES FOR C LAMPS - CONDITION A
Fig. 15



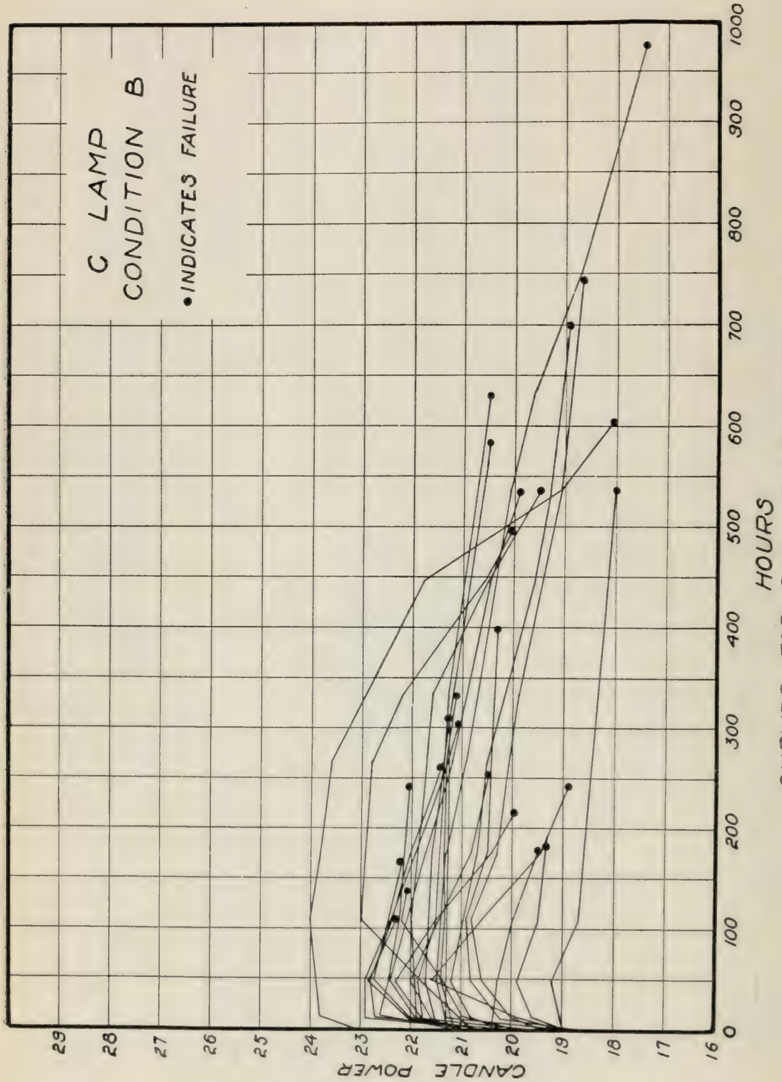
CURVES FOR D LAMPS – CONDITION A.

Fig. 16



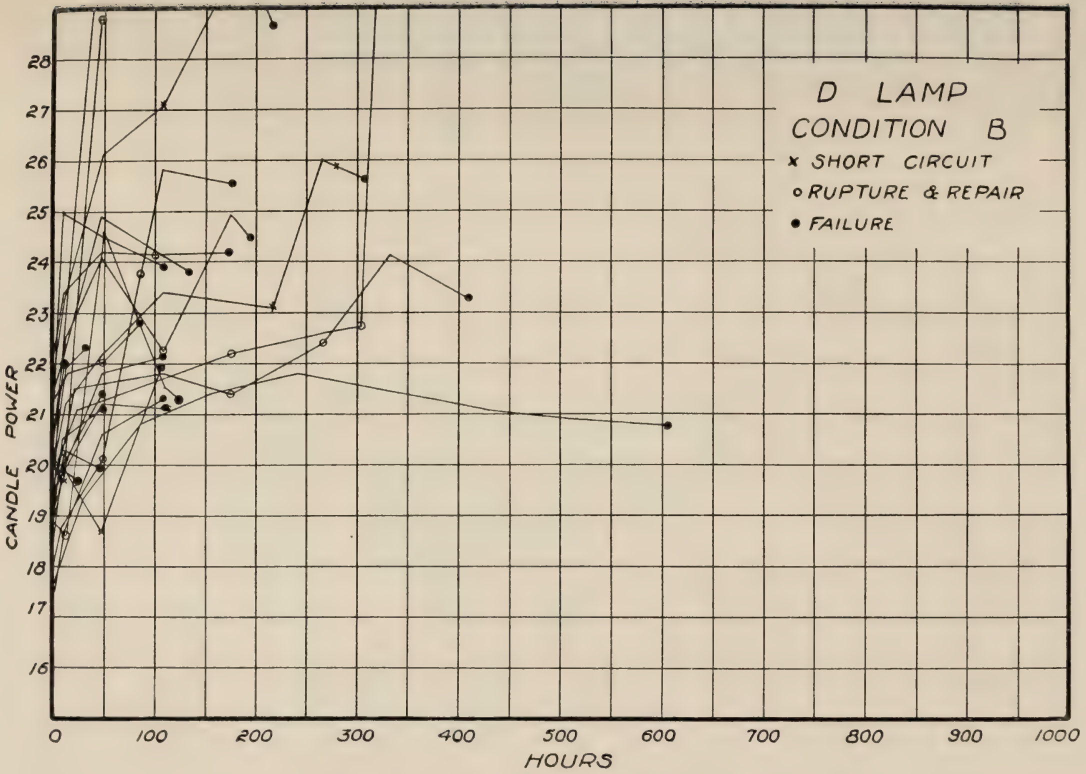
CURVES FOR P LAMPS - CONDITION A

FIG. 17



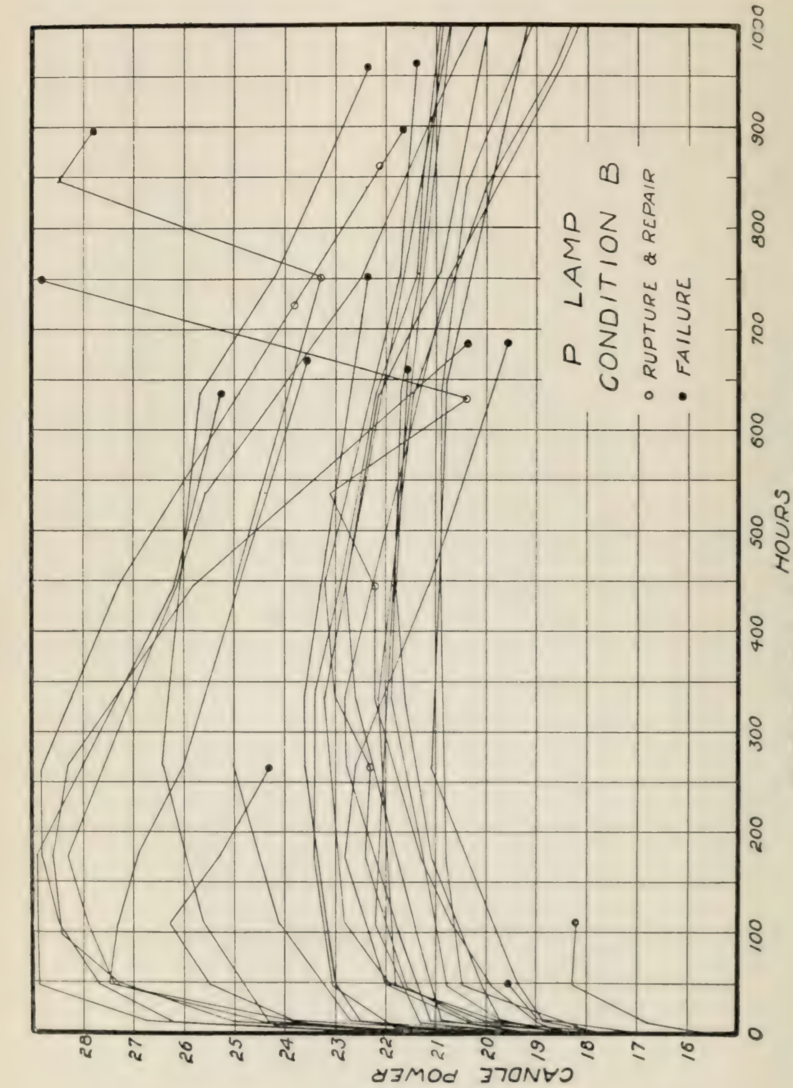
CURVES FOR C LAMP - CONDITION B.

Fig. 18



CURVES FOR D LAMP-CONDITION B.

FIG. 19



CURVES FOR P LAMP — CONDITION B

FIG. 20

en filament can be repaired. For this reason, the curves for this lamp are very uniform, not showing the sudden increases and decreases that occur in the other lamps. In the *D* lamp the filaments can easily be welded when broken, in fact it is seldom that they can not be repaired after the first rupture. The sudden increases of candle-power that are so often noticeable in the curves for this type of lamp are caused by the welding and consequent decreases in the length of the filament.

In the *C* lamp, failures commenced after about 100 hours of burning and continued steadily for about 1500 hours, when all the lamps but one were gone. Failures in the *D* lamp began at about 300 hours, and at 1900 hours only one was burning. With the *P* lamp, there was one failure at about 300 hours, and then no more until after 900 hours, when they commenced to fail at the rate of about one every hundred hours.

Compared with the results under condition A, those under condition B are rather surprising. The *D* lamp, which made a satisfactory showing under good conditions of operation, did very poorly indeed when operated under adverse conditions. At the end of 600 hours all the lamps were burned out, having an average life of only 153 hours. The *C* and the *P* lamps, as might be expected, gave poorer results than when burning under condition A, but gave a much better average life than the *D* lamps, averaging 434 and 898 hours respectively.

The explanation of the poor life of the *D* lamp under condition B is very simple. These filaments are strung so that they are under tension and the stem upon which they are mounted is supported between two spiral springs. The object of these springs is to absorb the vibrations to which the lamp may be subjected, but the springs are so strong and the stem itself is so light that instead of protecting the filament from the vibrations, they simply take them up and hold them persistently, and of course set the tightly strung filaments to vibrating also. Often some of the filaments of the lamps on test would be seen to vibrate like a violin string with an amplitude that would occasionally become great enough to allow the two sections of a filament to touch and short circuit themselves. A slight jar would often be sufficient to start these vibrations. It happens also that the tension, mass and length of some filament sections are such that when burned upon alternating current, persistent vibrations will be set up, due either to the presence of a stray[1] magnetic field or to the magnetic repulsion and attraction action of adjacent filament sections. Upon 50-cycle current, which is common in Germany where these lamps are manufactured, some filament sections would vibrate strongly when in a magnetic field, though there were fewer that would do so than there were on 60 cycles.

On account of being mounted without tension, the filaments of neither the *P* nor the *C* lamps would vibrate upon either the 60 or 50 frequency current, unless placed in a strong magnetic field, for instance, between the poles of a horse shoe magnet. When in a strong field, the filaments of both lamps formed a node in the middle and vibrated in two sections. After a long period of burning, the *P* lamp filaments would sometimes be sufficiently contracted to put some of the filament sections under tension, and then the same persistent vibrations would be noticed in them as in the *D* lamp.

VI. Candle-Power Maintenance and Change in Efficiency

The curves in Fig. 21 to 24 show the changes in candle-power and efficiency for the three lamps, the curves representing the mean performance of all the lamps tested. All three lamps show the increase in candle-power during the first few hours of burning, and the subsequent falling off in candle-power that is usual with incandescent lamps. The *P* lamp, however, shows the greatest change. It also maintains the highest average candle-power throughout the test, the *D* lamp being next and the *C* lamp the lowest. After 2000 hours' burning, the average candle-power of

---

[1] The only magnetic field that was near enough so that there was any possibility of its affecting the lamps was due to a direct current circuit carrying 7 amperes and it was at a distance of about 8 feet from the test rack so that its effect must have been very small.

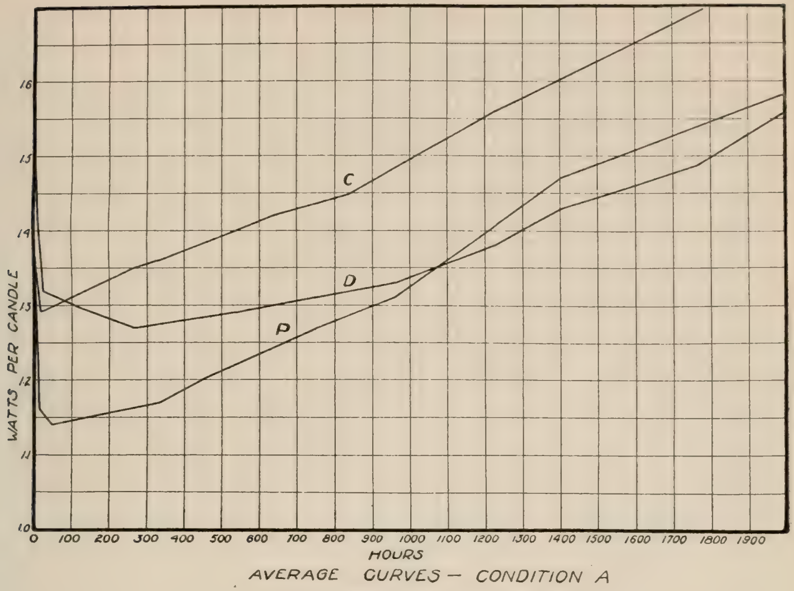

WATTS PER CANDLE
1.6
1.5
1.4
1.3
1.2
1.1
1.0
C
D
P
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
HOURS
AVERAGE CURVES — CONDITION A

FIG. 21

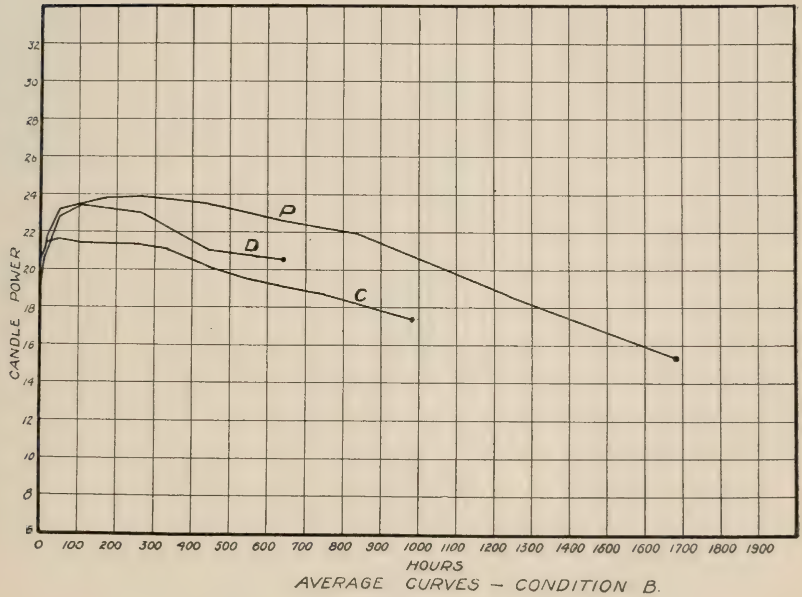
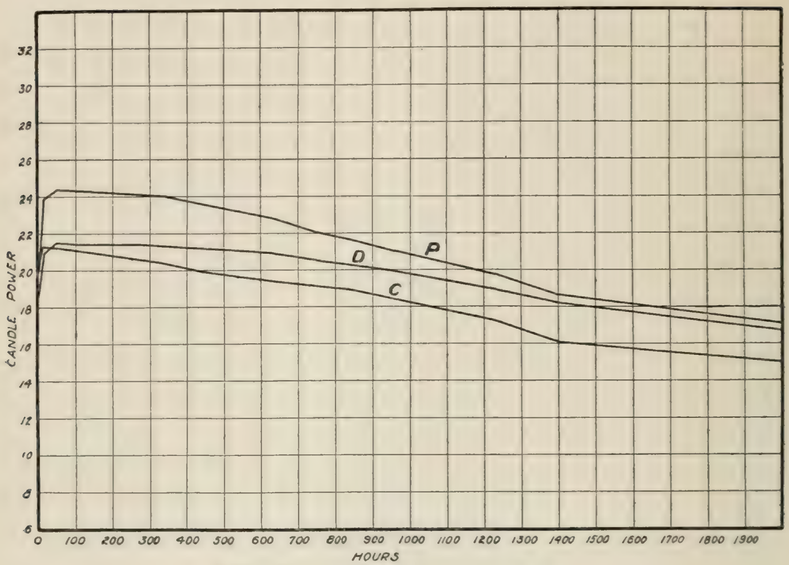
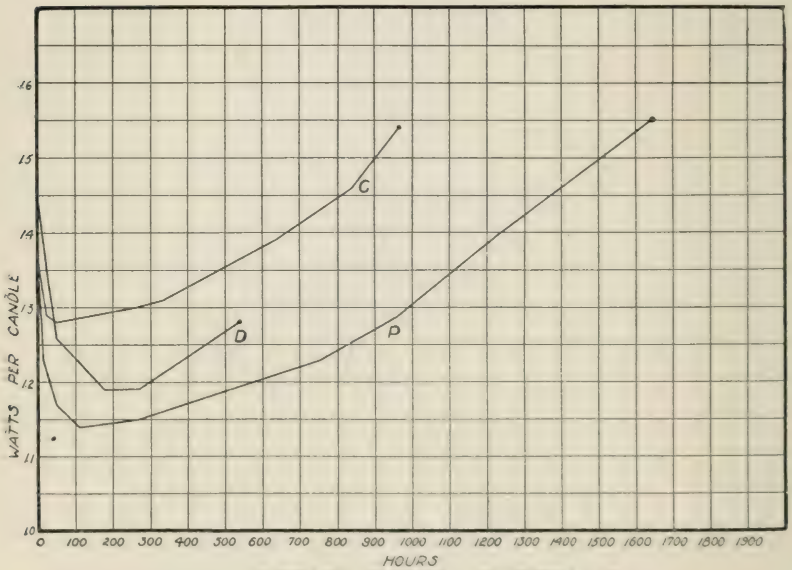

CANDLE POWER
32
30
28
26
24
22
20
18
16
14
12
10
8
6
P
D
C
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1600
1600
1700
1800
1900
HOURS
AVERAGE CURVES — CONDITION B.

FIG. 22



AVERAGE CURVES — CONDITION A

FIG. 23



AVERAGE CURVES CONDITION B

FIG. 24

the *P* lamps decreased to 88 per cent, the *D* lamps to 89 per cent and the *C* lamps to 77 per cent of the initial value.

The curves of average efficiency show the *C* lamp to have the highest watt per candle consumption throughout the tests. Up to about 1100 hours, the *D* lamp gives a poorer efficiency than the *P* lamp, but at this point the curves cross and the *D* lamp gives the better efficiency from that time on. This change in the relative efficiency of the two lamps is due to the greater blackening of the bulb of the *P* lamp.

Bulb Discoloration.—For the purpose of securing a standard by which the discoloration of the different lamps could be compared, a series of 10 carbon lamps was obtained from the Electrical Testing Laboratories of New York. These lamps had been burned for different periods and consequently carbon deposits of different densities were formed on the bulbs; they ranged in intensity from 95 per cent of the original candle-power down to 66.9 per cent. They were numbered from 1/2 to 5 as shown below.

TABLE 3

Lamp No......	1/2	1	1 1/2	2	2 1/2	3	3 1/2	4	4 1/2	5
Per cent C. P..	95	91.3	86.9	83	78.6	75.3	73	70.5	68.7	66.9

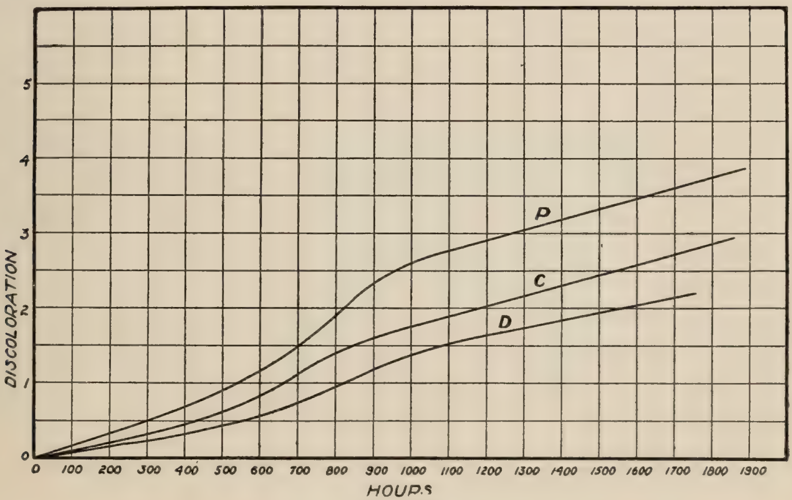


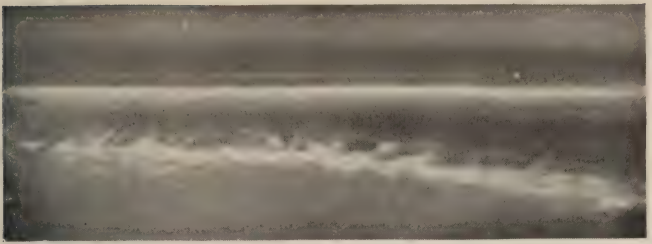
FIG. 25

At intervals throughout the life test, the color of each tungsten lamp was compared with that of the series of carbon lamps, and the number with which it matched in color was noted. In this way the rapidity with which the tungsten lamps blackened could be determined. The lamps did not blacken uniformly over the surface, hence the darkest portion was always chosen for comparison. Fig. 25 shows the results obtained. It is plotted between hours of burning and discoloration and represents the average results of 25 lamps of each kind. The *P* lamp shows the most pronounced discoloration while the *D* lamp shows the lowest. The *P* lamps were decidedly non-uniform in the rapidity with which they blackened. Some of them would be discolored scarcely any after 1000 or 1500 hours' burning, while the others would be as black as the No. 5 carbon lamp. The *C* and *D* lamps seemed to blacken uniformly, so that at any time all of the lamps of either of these types would be discolored approximately the same amount.

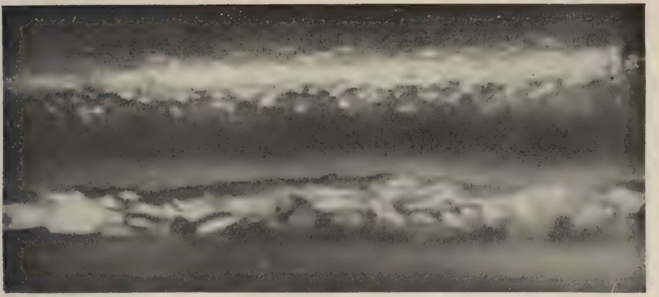
In Fig. 26 are microphotographs showing the condition of the filaments after a long period of burning. In each case a new filament is shown for comparison. As might be expected, all three filaments become much roughened and pitted after a period of burning, and decrease somewhat in size, the *D* filament to a considerable extent. Filaments burned upon alternating current are the same in appearance as those burned upon direct current for the same length of time and do not show the segmentation that takes place in tantalum filaments.

A summary of the performance of the lamps on the life and efficiency tests is shown in Table 4. The curves in Fig. 27 and 28 are plotted between "Total cost in cents per candle-power-hour for lamps and energy" as ordinates and "Cost of energy per kilowatt-hour" as abscissas. The curves for condition A are drawn from calculations based upon a 2000-hour test and those for condition B from calculations based upon a 1000-hour test.

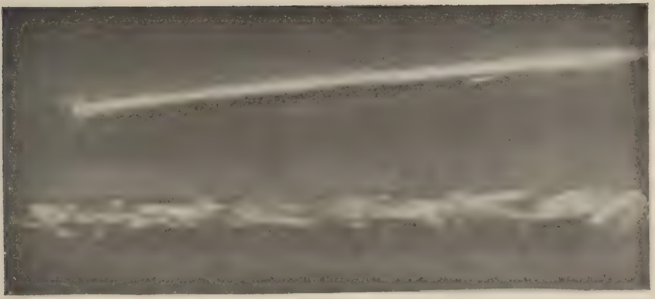
On account of the lower cost of lamp and the fewer burnouts, the *P* lamp gives a considerably lower total cost of operation than the other two. The cost of operating the *D* lamp under condition



C Filament

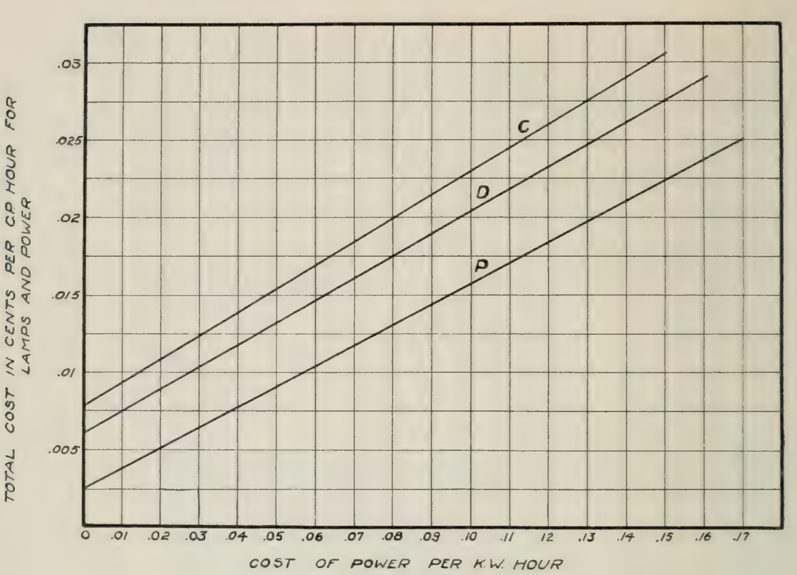


D Filament



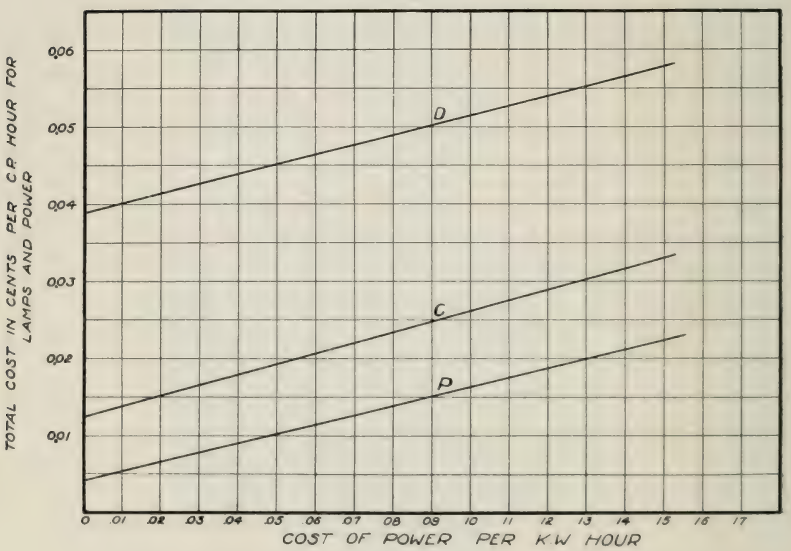
P Filament

Fig. 26



Condition A

FIG. 27



Condition B

FIG. 28

TABLE 4

SUMMARY OF LIFE AND EFFICIENCY TESTS

Lamp	*C*		*D*		*P*	
Operating Condition	A	B	A	B	A	B
Av. Mean Horizontal C. P.						
a. New	19.9	20.6	18.6	19.9	19.9	19.3
b. 1000 hours	18.2		19.7		20.8	20.6
c. 2000 hours	15.0		16.7		191	
Spherical Reduction Factor	.840		.730		.785	
Av. Watts per Lamp	27.5	27.4	28.0	28.0	27.7	27.0
Av. Initial Watts per C. P.	1.36	1.36	1.48	1.44	1.32	1.32
Av. Life in Hours	762	434	1167	153		898
Av. C. P. through Life	18.2	20.2	19 5	22.5	20.9	22.5
Cost Lamps to run 1000 hrs.		$62.64		$220.05		$23.80
" " " 2000 "	$70.28		$58.05		$25.50	
C. P. Hours per Lamp	36,400	20,200	39,000	22,500	41,800	22,500
Total C. P. Hours	910,000	505,000	975,000	562,000	1,045,000	562,000
Kilowatt Hours	1,375	685	1,400	700	1,385	675
Cost of Lamps	$1.08		$1.35		$.85	

B is excessively high on account of the exceedingly short average life of the lamps under this condition; in fact, for power costs below 12 or 13 cents per kilowatt-hour, they are more expensive to operate than ordinary carbon filament lamps.[1]

VII. CONCLUSIONS

Comparisons of the durability of filaments made by the colloid, deposition and paste processes are very difficult to make owing to the fact that the three types were all mounted differently. Undoubtedly the manner of mounting a filament has a great effect upon its life, and whether the superior life of one type of lamp is due to the fact that it has a better scheme of mounting or to the fact that the process of manufacture is better, can hardly be decided definitely from these tests. Tests of filaments made by the three processes and mounted in exactly the same way would be necessary to decide this question absolutely. From the tests just described, however, the colloid process seems to give a filament that is less durable than the other two. It is true that when tested under condition B, it gave a longer life than did the *D* lamp, but this was because its construction enabled it to withstand vibration better rather than because of the superior quality of the filament. Under condition A where vibration was eliminated and where the scheme of mounting had less effect upon the life, the *D* lamp gave a considerably longer life. The *P* lamp gave a much better life under both conditions of operation than the *C* and *D* lamps. This must be due at least in part to the fact that the filament has better lasting qualities than those made by the other processes. Under condition A, this lamp shows the same superior life as it did under condition B where differences in mounting produce great differences in average life.

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[1] In Engineering Experiment Station Bulletin No. 19 are given the results of tests upon carbon, metallized carbon and tantalum lamps which may be compared with the results given in this bulletin for tungsten lamps. It should be said, however, that the metallized carbon and tantalum lamps used for the tests described in Bulletin No. 19 were manufactured three or more years ago and that lamps of these kinds now manufactured and put upon the market show a considerable improvement over the ones tested.

Of the three schemes for mounting the filaments, that of the *C* lamp undoubtedly holds the filament more nearly in the desired place for all positions of burning than the other two. While holding it in the proper position, it at the same time holds it loosely enough so that all necessary contraction can take place without putting it under a tension that is likely to cause it to respond readily to vibrations. The principal defects of this scheme of mounting are that it lacks simplicity and that there are a large number of supporting spires that carry off by heat conduction energy that should be radiated in the form of light. For burning in a vertical pendant position or nearly so, the mounting of the filament in the *P* lamp is very good. The filament is held loosely so that contraction can take place without putting it under sufficient tension for vibration to have the serious effect upon it that it does upon the *D* filament. When burning horizontally it sags considerably, often enough to allow it to touch the glass stem supporting it. This at least gives the lamp a poor appearance even if it caused no other bad effects. The mounting of the *D* filament permits almost no distortion of the filament to take place when burning horizontally, but it has the serious fault of holding the filament in tension so that it responds readily to vibrations. The spring suspension of the supporting stem tends to make worse the very thing that it is intended to prevent. No doubt there would be less trouble from vibration with this style of filament mounting if the stem were rigid. That there would still be bad effects from vibration even if the stem were rigid is proved by the *P* lamp. When a filament section in this lamp, which has a rigid stem, contracted sufficiently to put it under tension, as sometimes happened, it would respond to vibrations when burning under condition B in the same way that the *D* filament did, and then quickly fail. A considerable number of the newer tungsten lamps coming on the market have their filaments mounted under a slight tension, just as in the *D* lamp, but where they are to be subject to vibration, it is doubtful if they will give as good results as more loosely strung filaments would.

These tests show that the performance of tungsten lamps may vary to a surprising degree depending upon the kind of lamps used and upon the conditions under which they are burned. Some lamps will give as high operating cost as the old carbon lamps while burning under certain conditions, whereas other lamps will give good results under those same conditions. Under the best conditions, however, the tungsten lamps now on the market give excellent results. Their efficiency is maintained in a remarkable way and the life is very long, often several times what they are advertised to give.

Breakage in shipment and handling have been reduced to a small fraction of what was common in the early lamps. Only three of the three hundred lamps which were purchased for these tests were received with broken filaments, and although the lamps on some of the tests which have been described were handled dozens of times, almost no trouble was experienced so far as the breakage of filaments was concerned.

The other defect of the early lamps, that of early blackening of the bulbs, seems to have been overcome. Not one of the lamps on the tests showed any early discoloration at all, in fact, not until after about 600 hours of burning did any of the bulbs show an appreciable amount of blackening.

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print*).

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905. (*Out of print*).

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. (*Out of print*).

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906. (*Out of print*).

Circular No. 3. Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S .G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907, by L. P. Breckenridge and Paul Diserens. 1909.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (*Out of print*).

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906. (*Out of print*).

Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906. (*Out of print*).

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr, and Henry B. Dirks. 1906.

Bulletin No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906. (*Out of print*).

Bulletin No. 9. An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906. (*Out of print*).

Bulletin No. 10. Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print*).

Bulletin No. 11. The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907. (*Out of print*).

Bulletin No. 12. Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print*).

Bulletin No. 13. An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.

Bulletin No. 14. Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print*).

Bulletin No. 15. How to Burn Illinois Coal without Smoke, by L. P. Breckenridge. 1908.

Bulletin No. 16. A Study of Roof Trusses, by N. Clifford Ricker. 1908.

Bulletin No. 17. The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1908. (*Out of print*).

Bulletin No. 18. The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1908.

Bulletin No. 19. Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908. (*Out of print*).

Bulletin No. 20. Tests of Concrete and Reinforced Concrete Columns, Series of 1907, by Arthur N. Talbot. 1908. (*Out of print*).

Bulletin No. 21. Tests of a Liquid Air Plant, by C. S. Hudson and C. M. Garland. 1908.

Bulletin No. 22. Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. 1908.

Bulletin No. 23. Voids, Settlement and Weight of Crushed Stone, by Ira O. Baker. 1908.

Bulletin No. 24. The Modification of Illinois Coal by Low Temperature Distillation, by S. W. Parr and C. K. Francis. 1908.

Bulletin No. 25. Lighting Country Homes by Private Electric Plants, by T. H. Amrine. 1908.

Bulletin No. 26. High Steam-Pressures in Locomotive Service. A Review of a Report to the Carnegie Institution of Washington. By W. F. M. Goss. 1908.

Bulletin No. 27. Tests of Brick Columns and Terra Cotta Block Columns, by Arthur N. Talbot and Duff A. Abrams. 1909.

Bulletin No. 28. A Test of Three Large Reinforced Concrete Beams, by Arthur N. Talbot. 1909.

Bulletin No. 29. Tests of Reinforced Concrete Beams: Resistance to Web Stresses, by Arthur N. Talbot, 1909.

Bulletin No. 30. On the Rate of Formation of Carbon Monoxide in Gas Producers, by J. K. Clement, L. H. Adams and C. N. Haskins. 1909.

Bulletin No. 31. Fuel Tests with House-heating Boilers, by J. M. Snodgrass. 1909.

Bulletin No. 32. Occluded Gases in Coal, by S. W. Parr and Perry Barker. 1909.

Bulletin No. 33. Tests of Tungsten Lamps, by T. H. Amrine and A. Guell. 1909.

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 34 MAY 1909

TESTS OF TWO TYPES OF TILE-ROOF FURNACES UNDER A WATER-TUBE BOILER

BY J. M. SNODGRASS, ASSISTANT PROFESSOR OF MECHANICAL ENGINEERING, ENGINEERING EXPERIMENT STATION

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I. Introduction 2
II. Summary and Conclusions 5
III. Fuel 6
IV. Equipment 7
V. Method of Conducting the Tests 9
VI. Discussion 11
VII. Data and Results 17

I. INTRODUCTION

1. *Purpose of Tests*

The tests were made for the purpose of comparing boiler performance when operating with two types of furnace roofs.

2. *Two Types of Furnace Roofs*

The essential difference between the two furnace roofs employed consisted in the fact that in one case the tubes of the lower row were completely surrounded by the tile which formed the roof of the furnace, while in the other case the roof tile rested upon the tubes of the lower row, leaving the lower half of the tubes directly exposed to the flames and hot gases arising from the fire bed. This difference and the construction of the two types of roof are shown in Fig. 1, 2, and 3.

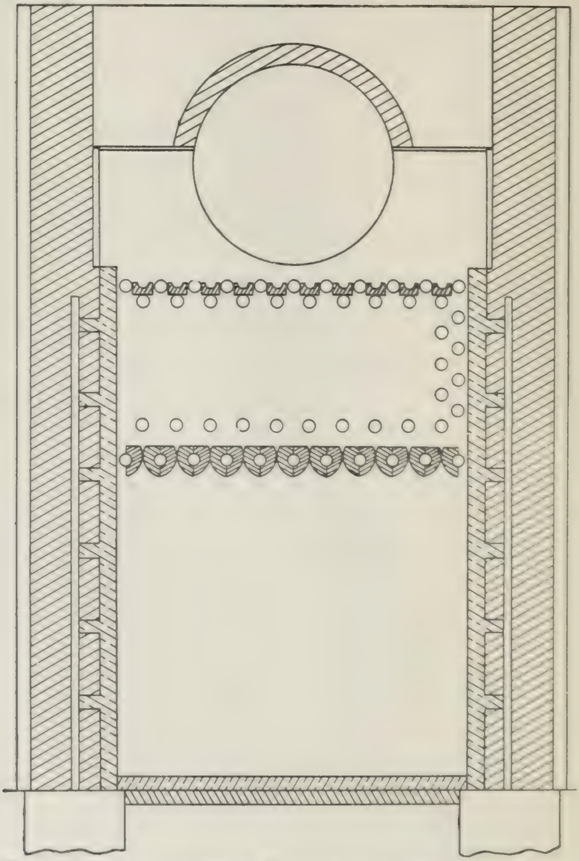

FIG. 1 CROSS-SECTION SHOWING CONSTRUCTION OF FURNACE ROOF AS MADE FROM *C* TILE

Fig. 1 shows in cross-section the roof in which the tile used completely encircled the tubes and prevented the flames and hot gases from coming in direct contact with the water-heating surface until they had traveled to the rear end of the furnace roof. This type of roof has been designated as the *C* tile roof.

Fig. 2 shows in cross-section the roof in which the roof tile rested upon the tubes, covering their upper surface only, leaving the lower surface of the tubes to be acted upon directly by the flames and hot gases arising from the fire-bed. This type of roof has been designated as the *T* tile roof. Strictly speaking, this roof would not be considered a tile roof, if, by the term tile roof, is

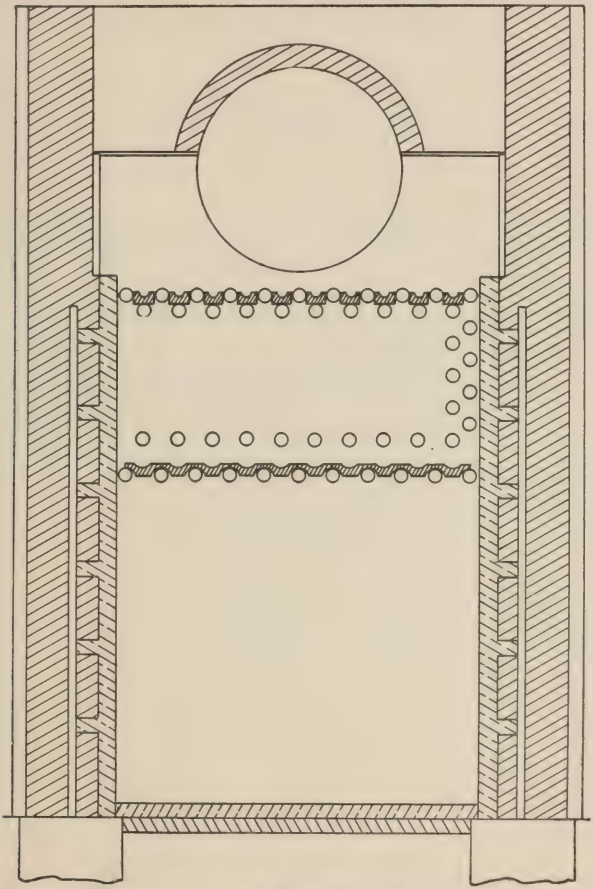

Fig. 2 Cross-section Showing Construction of Furnace Roof as Made from *T* Tile

meant a roof which presents to the fire a surface composed entirely of tile.

Fig. 3 is a longitudinal section showing the general arrangement of furnace and boiler. This shows the *C* tile roof in position. For the tests with the *T* tile, no changes were made except to remove the *C* tile, as shown in Fig. 3, replacing them with *T* tile. The first two rows of tile, crosswise of the boiler, and immediately back of the front water-leg consisted of *T* tile during all of the tests, as shown in the longitudinal section with the *C* tile roof in place, Fig. 3. These two rows of *T* tile facilitated the cleaning and inspection of the front end of the tubes.

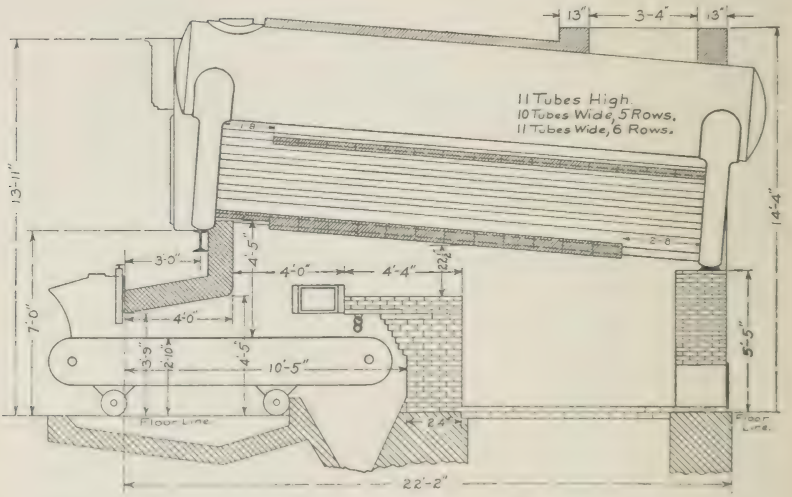

FIG. 3 LONGITUDINAL SECTION SHOWING ARRANGEMENT OF BOILER AND FURNACE

II. SUMMARY AND CONCLUSIONS

(*1*) Eight tests were made upon two types of roofs, four with each type.

(*2*) The minimum capacity developed for any one test was 102 per cent of rated capacity, and the maximum, 106 per cent of rated capacity.

(*3*) For the tests with the *C* tile roof, the boiler efficiencies varied from 64.4 per cent to 66.3 per cent with an average of 65.6 per cent. For the *T* tile roof tests the efficiencies varied from 67.5 per cent to 69.4 per cent with an average of 68.6 per cent. This shows a gain of 3 per cent in the boiler efficiency in favor of the *T* tile roof.

(*4*) The gain in water evaporated per pound of combustible is 5 per cent more when using the *T* tile than when using the *C* tile.

(*5*) The temperatures in the furnace and combustion chamber are from 200° to 400° F. less when using *T* tile than when using *C* tile. This condition should make radiation losses less when the roof is made of *T* tile. Maintenance of furnace, boiler and setting should be easier and less expensive with the *T* tile due to the lower temperatures. Lower flue gas temperatures are obtained when using *T* tile and are particularly of advantage when using induced draft apparatus.

The tests were not of sufficient length or at sufficiently high capacities to furnish data relative to the total life of such furnace roofs or to their relative effect upon boiler maintenance in many particulars. It is not uncommonly believed that with uncovered tubes, as with the *T* tile roof, at high capacities, there is much greater danger of injuring the tubes than with tubes covered, as with the *C* tile roof, and, consequently, greater difficulty in regard to boiler maintenance.

(*6*) Uniform and satisfactory fire conditions were more easily maintained during the tests with the *T* tile roof than with the *C* tile roof. It is possible that this condition may have been due entirely to other conditions than the difference in roofs.

(*7*) No smoke was made with the *C* tile roof and only smoke of a comparatively unobjectionable color when using the *T* tile roof. These results were at approximately 100 per cent of rated capacity. It is probable that the *C* tile roof could have been pushed to considerably higher capacities than the *T* tile roof without producing objectionable smoke.

(*8*) The *C* tile roof is superior to the *T* tile roof in the matter of smokelessness while the *T* tile roof is superior as regards simplicity, maintenance and efficiency.

III. FUEL

The coal as received was 1¼-inch screenings mined near Danville, Vermilion county, Illinois. In order to make it easier to maintain uniform conditions and to operate easily at 100 per cent rated capacity, or higher if desired, this coal, as it was shoveled from the car, was run over a ½-inch screen. In this way a large part of the very small coal was removed. The portion of the original coal which would pass through a ¼-inch screen averaged about 38 per cent and approximately this per cent of the coal was removed by screening as described above. On account of the coal being wetter in the cars during inclement weather than at other times, the screening process did not give entirely uniform results. As between the two series of tests, however, there was believed to be no appreciable difference in this respect at the time of conducting the tests.

Proximate chemical analyses of the coal used on each test with the calorific value will be found in Table 5, pp. 17, 18.

IV. EQUIPMENT

The tests were made upon a 210 horse-power water-tube boiler set over a chain grate stoker as shown in Fig. 3. This is the Engineering Experiment Station experimental fuel testing boiler and is similar to the boiler used at the U. S. G. S. testing plant at St. Louis, Missouri, and at Norfolk, Virginia. A number of the principal dimensions, not upon Fig. 3, are given in Table 1.

TABLE 1
DIMENSIONS OF ENGINEERING EXPERIMENT STATION FUEL TESTING BOILER

Kind of boiler		210 H. P. Heine water-tube
Kind of furnace		Green chain grate
Width of grate	inches	54
Length of grate	"	102
Grate surface	sq. ft.	38.25
Area of chimney	" "	8.7
Height of chimney above grate	feet	45.5
Kind of draft		Induced
Water heating surface	sq. ft.	2027
Number of tubes		116
Diameter of tubes, outside	inches	3.5
Ratio of water heating surface to grate surface,		53.1 to 1

Fig. 4, from a photograph, gives a view of the front of the boiler and of the induced draft apparatus, also the water weighing tanks, ash and coal cars, hoist and scales. The plant was especially designed for test purposes and is equipped with all apparatus ordinarily employed in such work. Descriptions of this plant have appeared in the bulletins of the Engineering Experiment Station in connection with work already reported.*

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*University of Illinois Engineering Experiment Station Bulletins No. 15; No. 36.

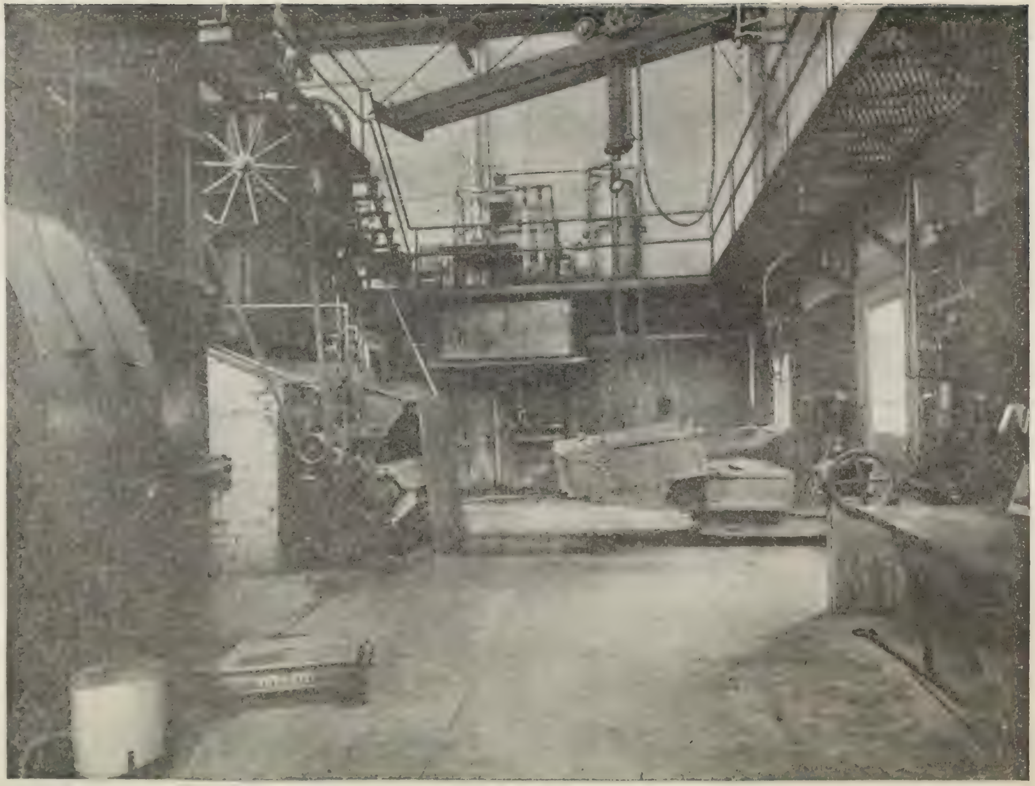

FIG. 4 GENERAL VIEW OF ENGINEERING EXPERIMENT STATION FUEL TESTING PLANT.
210 H. P. HEINE BOILER, WEIGHING TANKS, ASH CAR AND HOIST, INDUCED DRAFT.

V. Methods of Conducting the Tests

In general the methods as indicated by the A. S. M. E. code for conducting boiler trials were used.

(*1*) *Preparation.*—Before each series of tests, the boiler was washed out and the upper baffle of *U* tile thoroughly cleaned off. Before the tests with the *C* tile roof, the soot and ashes were removed from the upper side of the roof as thoroughly as possible by using the blower repeatedly from both ends of the boiler. The *T* tile roof was practically clean at the beginning of the tests, having been in use only about 24 hours previous to the first test. The boiler was blown down and the tubes blown off each night before the test of the following day. Fires were built up from the banked fire several hours before the beginning of a test, so that at the start operating conditions were uniform, and the boiler developing approximately its rated capacity.

(*2*) *Method of Starting and Stopping.*—The alternate method of stopping and starting the tests was used.

(*3*) *Firing.*—The coal fired was weighed out in lots of 500 lb. and record made both of the time consumed in burning each 500 lb. lot and of the amount of coal consumed during each hour of the test.

The opening between the grate and the lower edge of the gate measured 5¼ inches, for all tests, and the fuel bed thus admitted has been called 5 inches thick.

(*4*) *Feed Water.*—The amount of water fed to the boiler was determined by measuring tanks. The measuring tanks were set upon scales and measured weights were frequently checked by weighing.

(*5*) *Quality of Steam.*—The quality of the steam was determined with a throttling calorimeter.

(*6*) *Smoke Records.*—Smoke comparisons were made by means of the Ringlemann scale, No. 1, 2, 3, 4 and 5 representing respectively 20, 40, 60, 80 and 100 per cent of black smoke.

(*7*) *Flue Gas Samples.*—Flue gas samples were analyzed each hour, an average sample being collected over that interval of time. The sampling apparatus consisted of six ¼-in. sampling tubes distributed across the uptake. Samples were drawn from a junction box to which all of the sampling tubes were connected. Analyses were made with the Orsat apparatus.

(*8*) *Flue Temperatures.*—The flue temperatures recorded were taken at the center of the uptake at the same section from which the flue gas samples were drawn.

(*9*) *Water-back.*—The amount of water used by the water-back was measured by means of a meter which had been calibrated and found reliable over the range at which it worked.

(*10*) *Temperatures, Pressures and Drafts.*—Temperatures, pressures and drafts were recorded in the usual manner either with direct reading or recording instruments. Observations were in general taken every 20 minutes, although some observations were made at longer or shorter intervals, as seemed desirable in particular cases.

(*11*) *Furnace and Combustion Chamber Temperatures.*—Furnace and combustion chamber temperatures were taken at four places. These observations were taken hourly for all tests and during some tests at 20 minute intervals. Thermo-electric couples were employed which were capable of registering temperatures to about 2400° F. to 2500° F. before breaking down. Four such couples were used, two of which broke down during the tests, due to exposure to excessive temperatures. With four couples in service the four observations were taken consecutively during an interval of time amounting to one minute or less. When only two couples were in service they had to be transferred, and the time required to obtain the four observations amounted to several minutes. The couples used were compared with each other and with other pyrometers, although complete and satisfactory calibrations were not made. As compared with each other, the couples were quite uniform; while as compared with other pyrometers, the variation was from 0° to 50° F. All of the furnace and combustion chamber temperatures given are the same as those recorded, no corrections having been applied. They can be used for purposes of comparison as between different tests or series of tests or between temperatures at different parts of the setting. It is believed that most of the temperatures as recorded are correct within a variation of 50° F., that is, within either 25° above or below the recorded observation.

VI. Discussion

(*1*) *Uniformity of Conditions.*—Throughout all tests an effort was made to maintain conditions uniform except as such conditions might be affected by the two kinds of tile roof being used.

In two important items, draft and the amount of unburned fuel carried away in the refuse, there was some difference as between different tests.

The average draft in the uptake was 0.29 in. of water for the first test with the *C* tile, 0.43 in. of water for the second test and 0.35 in. for the other two tests. The lowest average draft for any test with the *T* tile was 0.31 in. of water, the highest 0.36 in., and 0.35 in. was the average draft for each of the other two tests.

The unburned fuel carried away in the ash and refuse was higher in the tests with the *C* tile than in those with the *T* tile. For the tests with the *C* tile the per cent of carbon in the ash and refuse varied from 30 per cent to 21 per cent, while for the tests with the *T* tile the corresponding figures were 22 per cent and 11 per cent. The better fire-bed conditions, indicated by the lower percentage of carbon in the ash for the second series of tests may have been due in part to better screened coal during the later tests, and to the fact that the men handling the boilers were becoming better accustomed to the work. Before any of the tests which have been reported were made, however, two preliminary tests of 10 hours each were run upon the two days preceding the first test reported. Throughout the tests no particular difficulty was experienced in maintaining apparently uniform conditions and operating at the capacity determined. The matter of coal screening is considered in the paragraph concerning fuel.

(*2*) *Evaporation and Efficiency.*—Table 2 presents results as to evaporative performance and efficiency. The equivalent evaporation per pound of combustible varies from 9.57 lb. to 9.88 lb. of water with the *C* tile roof in use and from 10.12 to 10.34 lb. of water with the *T* tile roof in use. The average for the *C* tile roof test is 9.76 lb. and for the tests with the *T* tile, 10.24 lb., an increase of 5 per cent for the *T* tile roof over the *C* tile roof. The boiler and furnace efficiency (not including the grate) shows an average efficiency of 65.6 per cent for the *C* tile tests and

68.6 per cent for the *T* tile tests, an increase of 3 per cent in the boiler efficiency. Corresponding figures based upon equivalent evaporation per pound of dry coal fired and upon plant efficiency, which include the action of the grate, show the results to have been about 8 per cent better in the case of the *T* tile tests than in the case of the *C* tile tests.

TABLE 2

EVAPORATIVE PERFORMANCE AND EFFICIENCY COMPARISON BETWEEN *C* AND *T* TILE-ROOF TESTS

Test No.	Equivalent Evaporation from and at 212° F. pounds				Efficiency per cent			
	Per Pound of Combustible		Per Pound of Dry Coal		Boiler and Furnace		Boiler, Furnace and Grate	
	C	*T*	*C*	*T*	*C*	*T*	*C*	*T*
1	9.88	10.23	7.48	8.07	66.3	68.6	60.5	65.4
2	9.57	10.34	7.56	8.37	64.4	69.4	61.5	67.5
3	9.78	10.12	7.82	8.37	65.9	67.5	62.0	66.1
4	9.80	10.26	7.63	8.31	65.8	68.8	61.9	67.3
Average	9.76	10.24	7.62	8.28	65.6	68.6	61.5	66.6

(*3*) *Combustible Consumed.*—Item 30, "total combustible consumed," was calculated by subtracting from the total dry coal fired, the ash as determined by chemical analysis and the combustible carried away in the refuse. In all calculated items in which combustible enters as a factor, this value has been used. Boiler efficiency values in particular are affected by the method in which the total combustible is computed.

(*4*) *Water-back.*—The amount of heat taken up by the water-back has not been considered in calculating the results. If all of the heat taken up by the water-back were assumed to have been returned to the boiler in the feed water without affecting conditions otherwise, the efficiencies so calculated would have been considerably higher. Table 3 gives a comparison of the efficiencies as calculated, and those calculated on the assumption that the heat taken up by the water-back was utilized by the boiler.

Had the assumption been made that a portion only of the heat taken up by the water-back should be credited to the boiler, the values for efficiency would have been found somewhere between the values given.

TABLE 3

COMPARISONS CONCERNING EVAPORATIVE PERFORMANCE AND EFFICIENCY WHEN CREDITING THE BOILER WITH ALL OF THE HEAT TAKEN UP BY THE WATER-BACK

	Test No.	Equivalent Evaporation from and at 212° F. per pound of Combustible, pounds		Efficiency of Boiler and Furnace (not including grate) per cent	
		No Credit Given Boiler for Heat Taken up by Water-back	Crediting All Heat Taken Up by Water-back to Boiler	No Credit Given Boiler for Heat Taken up by Water-back	Crediting All Heat Taken Up by Water-back to Boiler
C Tile Roof	1	9.88	10.16	66.3	68.2
	2	9.57	9.89	64.4	66.5
	3	9.78	10.07	65.9	67.9
	4	9.80	10.08	65.8	67.7
	Aver.	9.76	10.05	65.6	67.6
T Tile Roof	1	10.23	10.45	68.6	70.1
	2	10.34	10.52	69.4	70.6
	3	10.12	10.33	67.5	68.9
	4	10.26	10.50	68.8	70.5
	Aver.	10.24	10.45	68.6	70.0

(5) *CO_2 in Flue Gases.*—The average CO_2 content for all tests with the *C* tile roof was 6.8 per cent and for the tests with the *T* tile roof 7.5 per cent. CO was either not found in the flue gas or found only in small amounts. The lower CO_2 content for the *C* tile roof tests may have been due to poorer fire-bed conditions or to greater leakage of air through the setting during those tests.

(6) *Smoke.*—Except for the first test with the *C* tile roof, during which regular observations were not made, smoke observations were made at 10-minute intervals except as darkness prevented. Irregular observations for the first test gave "No smoke" for that test.

During the three tests upon which smoke observations were made with the *C* tile roof, 161 observations were recorded. One of these recorded smoke No. 1; 7 recorded smoke No. ½; and 153, no smoke. This is considered as smokeless operation.

During the four tests with the *T* tile roof, 233 observations were recorded. One observation of No. 2 smoke was made, which was the maximum recorded. As shown in Table 5, page 19, the average smoke recorded varied from 9 per cent to 17 per cent for the four tests. These percentages correspond approximately to No. ½ and No. 1 smoke by the Ringlemann scale.

The operation with the *C* tile roof was smokeless and higher capacities could doubtless have been obtained without trouble from this source. With the *T* tile roof, the operation as to smokelessness was quite satisfactory, no smoke of a blackness greater than No. 2 being recorded, and the average for all tests being well under No. 1. It was evident that had higher capacities been demanded, trouble with black smoke might have resulted.

(7) *Furnace, Combustion Chamber, Flue Temperatures.*—Table 4 presents the average temperatures as observed at four points in the combustion space and in the flue for each test, also averages for the four tests made with each type of roof.

It will be noted that the temperatures are uniformly lower for the *T* tile roof than for the *C* tile roof, the greatest average difference being 371° at a point in the combustion chamber.

Fig. 5 indicates the location of the openings for the insertion of the thermo-couples and the flue gas pyrometer. The couples extended in all cases about 14 in. into the furnace, measuring from the inside of the setting.

TABLE 4

Temperatures in Furnace, Combustion Chamber and Flue

Test No.	Temperatures—Degrees F									
	Pyrometer No. 1 In Furnace		Pyrometer No. 2 Over Bridge-wall		Pyrometer No. 3 Forward Part of Combustion Chamber		Pyrometer No. 4 Rear Part of Combustion Chamber		Pyrometer No. 5 In Uptake	
	C	*T*	*C*	*T*	*C*	*T*	*C*	*T*	*C*	*T*
1	2052	1893	2177	1873	2023	1636	1677	1409	549	496
2	2086	1870	2061	1830	1861	1625	1534	1418	565	484
3	2073	1869	2202	1845	2063	1530	1721	1325	563	458
4	2053	1902	2164	1855	1923	1595	1636	1384	556	432
Average	2066	1883	2151	1851	1968	1597	1642	1384	558	468
Difference	183		300		371		258		90	

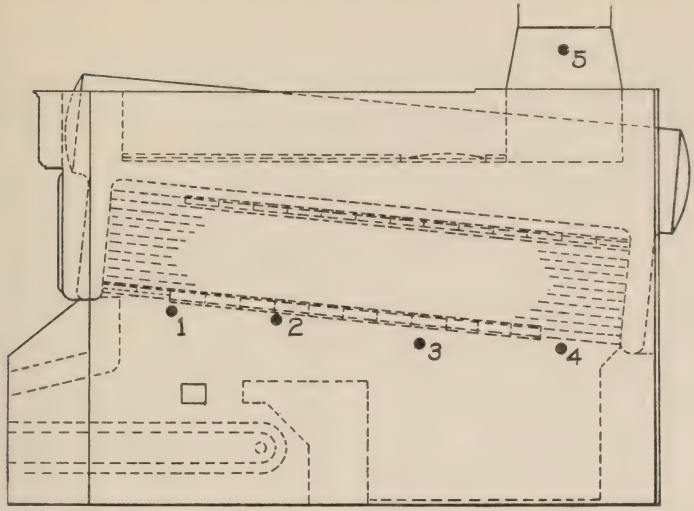

FIG. 5 SHOWING LOCATION OF HOLES FOR INSERTION OF THERMO-COUPLES AND FLUE-GAS PYROMETER

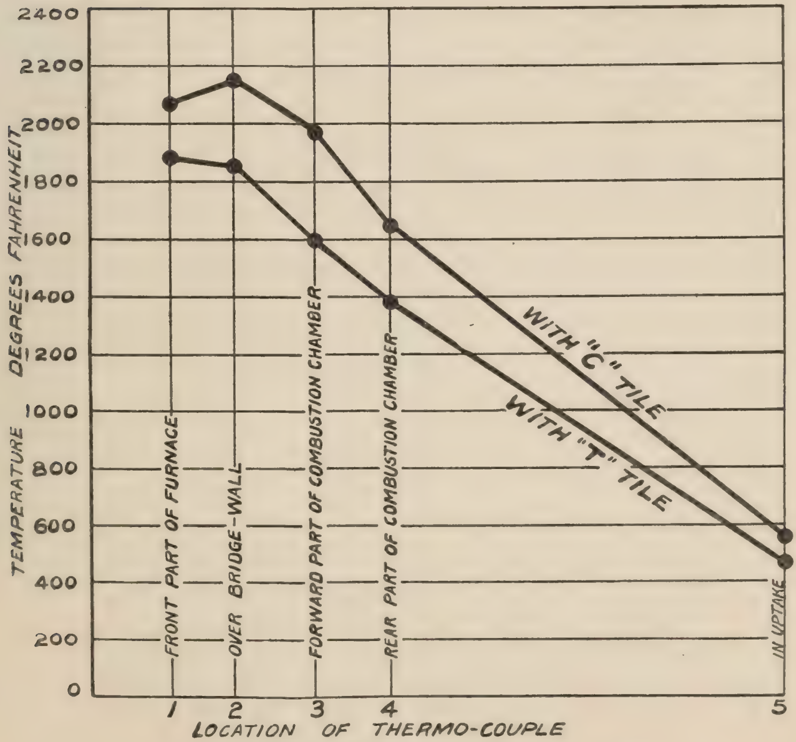

FIG. 6 AVERAGE TEMPERATURES FOR TESTS

In Fig. 6, there have been plotted the average values for all observations taken at the different points for each series of tests. The abscissæ represent approximately the distances of the points of observation from the front of the furnace.

The highest temperature recorded was 2450° F. One thermocouple was melted down and destroyed shortly after an observation of 2350° had been made from it. The breaking down temperature was not noted. All temperature observations were made at regular intervals. The fire at the time of making the 2450° observation and at the time of destroying the couple above referred to was apparently as hot as at any other time during the tests. During the *C* tile-roof tests, the furnace seemed to reach these temperatures a number of times. During the *T* tile-roof tests the temperatures were at all times considerably lower, the maximum temperature recorded being 2000° F.

VII. DATA AND RESULTS

Table 5 gives the principal data and results for the eight tests. Fig. 7 presents a graphical log for one of the tests with *C* tile roof and Fig. 8 a similar log for one of the tests with the *T* tile.

TABLE 5 DATA AND RESULTS

Comparative Tests with *C* and *T* Tile-Roof Furnaces

A.S.M.E. Code No.		*C* Tile-Roof Tests				*T* Tile-Roof Tests			
	Test Number	1	2	3	4	1	2	3	4
1	Date of Trial	Dec. 24, 1908	Dec. 29, 1908	Dec. 30, 1908	Dec. 31, 1908	Jan. 11, 1909	Jan. 12, 1909	Jan. 13, 1909	Jan. 14, 1909
2	Duration of Trial (hours)	10	10	10	10	10	10	10	10
	AVERAGE PRESSURES								
11	Steam pressure by gauge, lbs. per sq. in.	139	138	142	141	139	141	141	141
12	Force of draft between damper and boiler, inches of water	.29	.43	.35	.35	.35	.31	.35	.36
13	Force of draft in furnace, inches of water	.170	.165	.179	.160	.145	.124	.116	.130
	AV. TEMPERATURES								
15	Of external air, degrees	46	44	42	22	12	17	22	35
16	Of fireroom, degrees	68	70	66	65	64	71	74	72
20	Of feed water entering boiler, degrees	56	57	57	56	55	55	55	55
21	Of escaping gases from boiler, degrees	549	565	563	556	496	484	458	432
	FUEL								
25	Weight of coal as fired, lb.	11149	11000	11102	11092	10882	10340	10058	10438
26	Percentage of moisture in coal, per cent	11.27	11.00	12.13	12.84	12.78	12.72	12.60	12.25
27	Total weight of dry coal consumed, lb.	9893	9790	9755	9668	9491	9025	8791	9159
28	Total ash and refuse, lb.	2313	1721	1853	1860	1654	1376	1346	1374
30	Total combustible consumed, lb.	7489	7737	7802	7532	7490	7299	7270	7417
31	Percentage of ash and refuse in dry coal, per cent	23.38	17.58	19.00	19.24	17.43	15.25	15.31	15.00
	PROXIMATE ANALYSIS OF COAL AS FIRED								
32	Fixed Carbon, per cent	35.66	36.85	37.06	36.53	35.30	36.09	37.02	35.17
33	Volatile matter, per cent	37.91	36.83	37.71	35.62	36.83	36.55	36.73	37.52
34	Moisture, per cent	11.27	11.00	12.13	12.84	12.78	12.72	12.60	12.25
35	Ash, per cent	15.16	15.32	13.10	15.01	15.09	14.64	13.65	15.06
36	Sulphur, separately determined, per cent	3.51	5.24	4.03	4.10	4.14	4.29	3.79	4.72
43	Moisture in air dry sample, per cent	3.66	4.81	3.91	4.38	4.89	5.29	6.27	5.80
	ANALYSIS OF ASH AND REFUSE								
44	Carbon, per cent	30.81	21.31	26.92	25.31	21.71	15.45	10.96	12.39
45	Earthy matter, per cent	69.19	78.69	73.08	74.69	78.29	84.55	89.04	87.61

TABLE 5 Data and Results

Comparative Tests with *C* and *T* Tile-Roof Furnaces

A.S.M.E. Code No.		*C* Tile-Roof Tests				*T* Tile-Roof Tests			
		1	2	3	4	1	2	3	4
	Fuel Per Hour								
46	Dry coal consumed per hour, lb	989.3	979.0	975.5	966.8	949.1	902.5	879.1	915.9
48	Dry coal per square foot of grate surface per hour, lb	25.89	25.63	25.54	25.31	24.85	23.63	23.01	23.98
	Calorific Value of Fuel								
50	Calorific value by oxygen calorimeter, per lb. of dry coal, B.t.u	11935	11883	12194	11905	11911	11972	12223	11923
51	Calorific value by oxygen calorimeter per lb of combustible, B.t.u	14394	14354	14331	14381	14403	14384	14485	14393
	Quality of Steam								
54	Percentage of moisture in steam, per cent.	1.13	1.06	1.20	1.16	1.06	1.12	1.18	1.13
	Water								
57	Total weight of water fed to boiler, lb	61687	61759	63702	61524	63772	62882	61279	63370
58	Equivalent water fed to boiler from and at 212°, lb	74598	74610	76997	74419	77185	76125	74190	76716
59	Water evaporated, corrected for quality of steam, lb	61175	61277	63141	61001	63275	62366	60746	62844
60	Factor of evaporation	1.20930	1.20808	1.20870	1.20960	1.21032	1.21060	1.21070	1.21060
61	Equivalent water evaporated into dry steam from and at 212° (Item 59 × Item 60), lb	73979	74028	76319	73787	76583	75500	73545	76079
	Water per Hour								
62	Water evaporated per hour, corrected for quality of steam, lb	6117.5	6127.7	6314.1	6100.1	6327.5	6236.6	6074.6	6284.4
63	Equivalent evaporation per hour from and at 212°, lb.	7397.9	7402.8	7631.9	7378.7	7658.3	7550.0	7354.5	7607.9
64	Equivalent evaporation per hour from and at 212° per square foot of water-heating surface, lb	3.65	3.65	3.77	3.64	3.78	3.72	3.63	3.75
	Horse-Power								
65	Horse-power developed. (34½ lbs. of water evaporated per hour into dry steam from and at 212°, equals one horse-power), H. P.	214.4	214.6	221.2	213.9	222.0	218.8	213.2	220.5
66	Builders rated horse-power' H. P.	210	210	210	210	210	210	210	210
67	Percentage of builders' rated horse-power developed, per cent	102	102	105	102	106	104	102	105

TABLE 5 DATA AND RESULTS

Comparative Tests with *C* and *T* Tile-Roof Furnaces

A.S.M.E. Code No.		*C* Tile-Roof Tests				*T* Tile-Roof Tests			
		1	2	3	4	1	2	3	
	ECONOMIC RESULTS								
68	Water apparently evaporated under actual conditions per pound of coal as fired. (Item 57 ÷ Item 25), lb.	5.53	5.61	5.74	5.55	5.86	6.08	6.09	6.07
69	Equivalent evaporation from and at 212° per pound of coal as fired. (Item 61 ÷ Item 25), lb.	6.64	6.73	6.87	6.65	7.04	7.30	7.41	7.29
70	Equivalent evaporation from and at 212° per pound of dry coal. (Item 61 ÷ Item 27), lb.	7.48	7.56	7.82	7.63	8.07	8.37	8.37	8.31
71	Equivalent evaporation from and at 212° per pound of combustible. (Item 61 ÷ Item 30), lb.	9.88	9.57	9.78	9.80	10.23	10.34	10.12	10.26
	EFFICIENCY								
72	Efficiency of the boiler; heat absorbed by the boiler per lb. of combustible divided by the heat value of one lb. of combustible, per cent.	66.28	64.38	65.92	65.79	68.56	69.45	67.45	68.83
73	Efficiency of boiler, including the grate; heat absorbed by the boiler, per lb. of dry coal, divided by the heat value of one lb. of dry coal, per cent.	60.51	61.46	61.97	61.92	65.43	67.49	66.10	67.28
	COST OF EVAPORATION								
76	Cost of fuel used for evaporating 1,000 lbs. of water from and at 212°, with coal at $1.00 per ton of 2,000 lb.	.0753	.0743	.0728	.0752	.0710	.0685	.0675	.0686
	SMOKE OBSERVATIONS								
77	Percentage of smoke as observed, per cent.		0.	0.	1.	9.	11.	13.	17.
	ANALYSIS OF THE DRY GASES								
84	Carbon dioxide (CO_2), per cent.	7.5	5.1	7.7	7.0	6.7	7.7	7.7	7.9
85	Oxygen (O), per cent.	11.7	14.9	11.6	12.8	13.1	11.7	11.8	11.5
86	Carbon monoxide (CO), per cent.	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88	Nitrogen (by difference) (N), per cent.	80.7	80.0	80.7	80.2	80.2	80.6	80.5	80.6

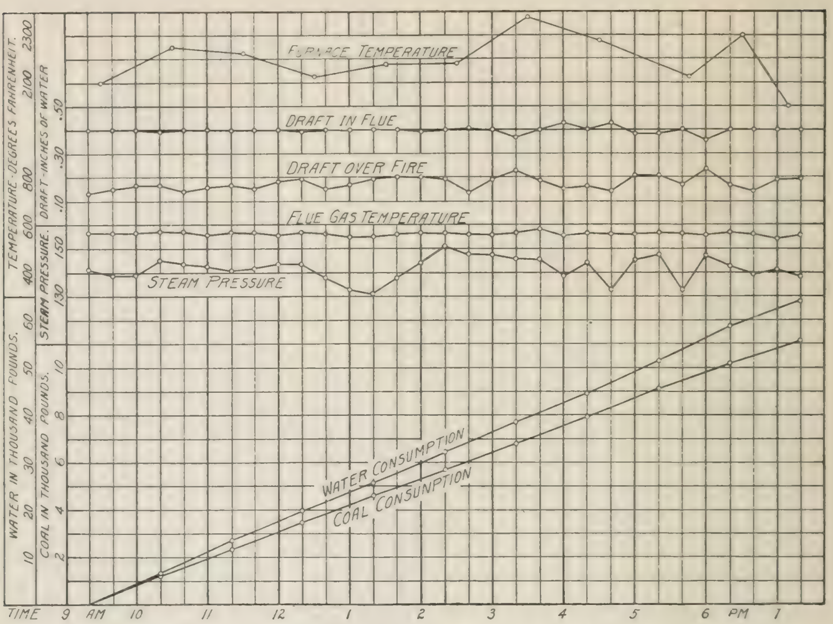

Fig. 7 Graphical Log for Test No. 3, *C* Tile

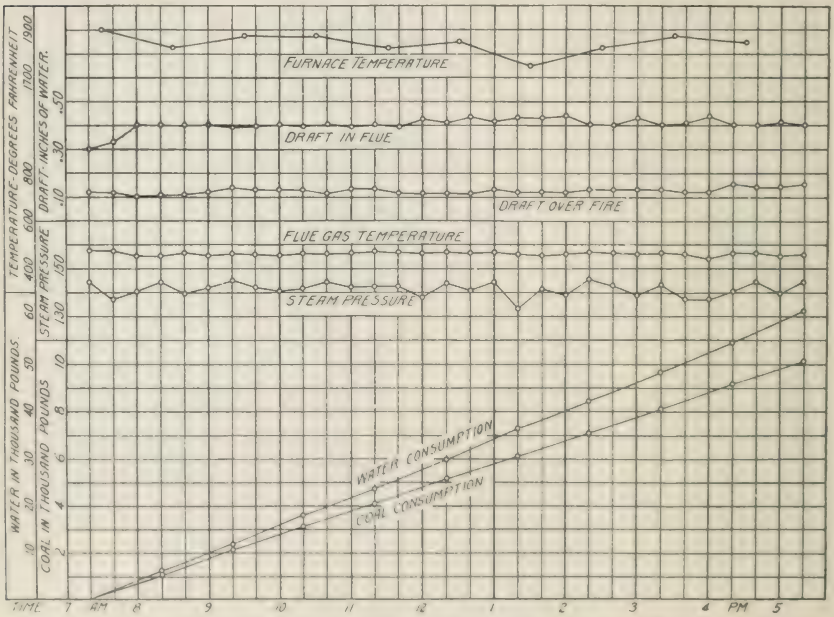

Fig. 8 Graphical Log for Test No. 3. *T* Tile

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Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905. (*Out of print*)

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Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906. (*Out of print*).

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Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906. (*Out of print*).

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UNIVERSITY OF ILLINOIS

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A STUDY OF BASE AND BEARING PLATES FOR COLUMNS AND BEAMS

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I. Introduction

The primary object of this study has been to produce a series of accurate formulas and tables for the different forms and materials of base and bearing plates. These formulas are required to be as simple and as easily applied as possible and to be in accordance with the local building ordinances of the larger cities in the United States.

A secondary purpose has been to devise a similar series of formulas based on the common theory of the fracture of such plates and to check the accuracy of these common formulas by experimental tests of a series of plates designed in accordance with such formulas. A number of typical plates were so designed and tested in 1907 by Mr. C. R. Dick, B. S. in Architectural Engineering, and the results were discussed in his thesis.

Up to the present time, very little study of theory and no experimental research appear to have been devoted to these plates. Even the German writers usually give incorrect theories with formulas based thereon, formulas which give erroneous dimensions of base plates.

II. Limit of Safe Pressure of Plate on Masonry

The maximum safe pressure of the plate on the masonry beneath it varies greatly, according to the nature and the resistance of this material; the requirements of the city building ordinances also differ considerably for the same kind of masonry. These requirements seem to be based upon local customs and not on actual experimental tests. Examples of such maximum safe pressures are here quoted from the ordinances of New York, Chicago and Washington, D. C., selected as representative cities, and these are further compared with the values given in Kidder's Pocket Book. (Table 1.)

Therefore this maximum safe pressure of the plate on masonry appears to vary between 70 and 1000 pounds per square inch, the larger value being allowed for truly dressed large blocks of stone. The value to be employed must be taken in accordance with the local building ordinance.

Table 1

Safe Pressures on Masonry in Pounds per Square Inch

Masonry	*N. Y.*	*Chicago*	*Wash'ton*	*Kidder*
Granite	......	173.61	1000–2400	1000
Limestone	......	173.61	700–2300	....
Sandstone	......	173.61	400–1600	400–700
Dimension stone, rough	......	138.89	....	....
Rubble in portland cement	138.89	......	140.	150–200
Rubble in natural cement	111.11	......	111.	....
Rubble in cement and lime	97.22	......	97.	....
Rubble in lime	94.44	......	70.	....
Brickwork in portland cement	208.33	173.61	250.	150–250
Brickwork in natural cement	......	125.	208.	....
Brickwork in cement and lime	159.72	......	160.	....
Brickwork in lime	111.11	90.28	111.	100–120
Concrete in portland cement	208.33	173.61	208–230	200.
Concrete in natural cement	111.11	......	111–125	....

III. MAXIMUM SAFE FIBER STRESS IN METAL OF PLATE

This maximum fiber stress in pounds per square inch occurs at either top or bottom of a plate of uniform thickness, or at the bottom of a cast-iron plate of tapered thickness. It must not exceed the intensities given in the following table, which are almost uniformly adopted throughout the United States.

Table 2

Maximum Safe Fiber Stress in Plates

Metal	*N. Y.*	*Chicago*	*Wash'ton*	*Kidder*
Steel, compression	16 000	16 000	16 000	16 000
Steel, tension	16 000	16 000	16 000	16 000
Wrought Iron, compression	12 000	12 000	12 000	12 000
Wrought Iron, tension	12 000	12 000	12 000	12 000
Cast Iron, compression	16 000	10 000	16 000	......
Cast Iron, tension	3 000	2 500	3 000	......

Evidently the maximum tensile stress in cast-iron permitted in Chicago might safely be increased from 2500 to 3000 pounds per square inch, which is permitted in about one-half the cities in the United States.

IV. COMMON FORMULAS

The ordinary formulas for base plates are usually empirical (Kidder) or they are otherwise based on the theory that the line of fracture of a base plate is a straight line tangent to the exterior of the foot of the column standing on the plate (Kohnke). In accordance with this theory, a series of formulas was deduced and later published in the Handbook of the Chicago Architects' Business Association. The essential formulas are the following:

A. For Steel Plates of Uniform Thickness

Let p = maximum safe pressure of plate on masonry in lb. per sq. in.
k = perpendicular distance in inches from column to edge of plate.
t = thickness of plate required, in inches.

(a) For square plates (Fig. 1)

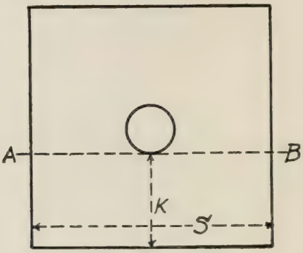


FIG. 1

The line AB (Fig. 1) is the theoretical fracture line.

Then $$t = \frac{k}{40}\sqrt{\frac{p}{10}} \qquad (1)$$

(b) For octagonal plates (Fig. 2)

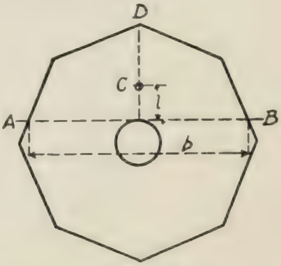


FIG. 2

The segment ADB may be divided into triangles, when its center of gravity C is easily found by graphical methods. (See Graphic Statics.)

Let l = perpendicular distance in inches from C to line of fracture AB.

b = length in inches of line of fracture.

a = area in square inches of the segment ADB outside the line AB.

Then
$$t = \frac{1}{40}\sqrt{\frac{3\,apl}{5\,b}} \qquad (2)$$

(*c*) For circular plates (Fig. 3)

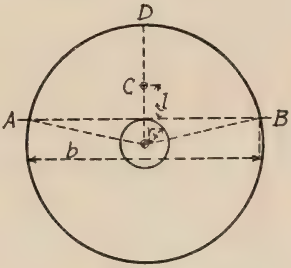


Fig. 3

Join the ends A and B of the chord fracture line with the center O by the radii AO, OB, and draw OD perpendicular to AB.

Let β = angle AOB in degrees between radii AO, BO.

A = area in square inches of the entire circle of the plate.

b = length in inches of chord fracture line AB.

R = external radius of end of column in inches.

Then $\frac{A\,\beta}{360}$ = area of the sector $ADBO$ in square inches.

$\frac{bR}{2}$ = area in square inches of triangle ABO.

Hence $\frac{\mathrm{A}\,\beta}{360} - \frac{bR}{2} = \mathrm{a}$ = area in square inches of segment ADB.

Also $\frac{b^3}{12\,a}$ = distance in inches from center O to center of gravity C of the segment.

Hence $l = \frac{b^3}{12\,a} - R$ = perpendicular distance in inches from C to chord line of fracture AB.

Finally,
$$t = \frac{1}{40}\sqrt{\frac{3\,apl}{5\,b}} \qquad (3)$$

B. For Cast-iron Plates of Tapered Thickness

Such plates are of uniform thickness only beneath the end of a column or beam, and are flat on the under side, but are beveled off on top from column to edge of the plate. These edges are usually made at least ⅜-in. thick, and a good rule is to make the edge one-fourth the thickness at the middle. These formulas are deduced for sharp edges or a trapezoidal fracture section, and they are therefore only approximate for plates with thick edges.

(*a*) For square plates (Fig. 4)

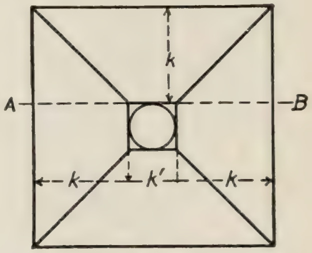


FIG. 4

Let k = projection of the edge of the plate outside the column, measured in inches and perpendicular to the edge.

k' = side in inches of square on top of plate and tangent to column.

The line of fracture AB is parallel to a side.

The thickness in inches of plate at middle is then given by the formula

$$t = \frac{k}{50}\sqrt{\frac{6\,p\,\left(k + \frac{k'}{2}\right)}{k + k'}} \qquad (4)$$

(*b*) For octagonal plates (Fig. 5)

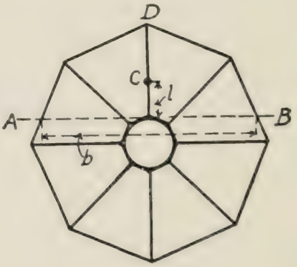


FIG. 5

In the manner already explained for the octagonal steel plate may be found the area a of the segment ADB, its center of gravity C, and the distance l.

The thickness in inches at the middle is then approximately

$$t = \frac{1}{50}\sqrt{\frac{12\,apl}{b}} \tag{5}$$

(c) For circular plates (Fig. 6)

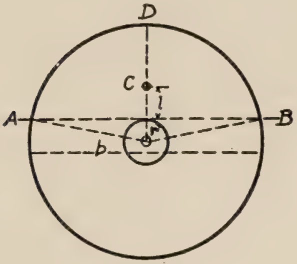


FIG. 6

As for circular steel plates:

$a = \frac{A\,\beta}{360} - \frac{bR}{2} =$ area in square inches of segment $\overset{\frown}{ADB}$.

$l = \frac{b^3}{12\,a} - R =$ perpendicular distance in inches from C to line AB. The actual fracture section lying between a very flat hyperbola and its chord, a parabola may be substituted therefor without material error.

The thickness at middle is given by the formula

$$t = \frac{1}{50}\sqrt{\frac{35\,apl}{8\,b}} = \frac{1}{23.9}\sqrt{\frac{apl}{b}} \tag{6}$$

V. RESULTS OF TESTS BY C. R. DICK

Employing the preceding formulas, Mr. C. R. Dick designed in 1907 a series of square, octagonal and circular plates of steel and of cast iron, and afterwards tested them in the testing laboratory of the University.

Each plate had a bottom area of 400 sq. in. and transmitted the very moderate safe pressure of 50 lb. per sq. in., making a total maximum safe pressure of 20 000 lb. for the entire plate. The thickness of each plate was made such that the maximum safe fiber stress in the fracture section produced by this maximum safe pressure should not exceed 16 000 lb. for steel or 2500 lb. for cast iron in tension, as required by the Chicago ordinance.

The distribution of the pressure of the plate uniformly over the lower surface required some form of elastic cushion between the plate itself and the very rigid bed of the testing machine. A cushion was composed of several folded blankets, a folded woollen comfortable and two thicknesses of rubber packing, but it failed under moderate pressures, though not sufficiently to seriously injure the plates except in the case of the cast iron. (Fig. 7). A cushion of dry sand forming a layer 2 inches thick was enclosed within a steel hoop a little larger than the plate, but the sand packed irregularly and failed to transmit a uniform pressure. A satisfactory cushion was finally composed of 11 layers of oak pieces, cut 24 x 3 x 7/8 in. piled in crosswise layers, leaving 1/4 in. spaces between the pieces to permit expansion. (Fig. 8). This cushion proved to be sufficiently elastic and also able to sustain pressures sufficient to break the cast-iron plates. Indeed it later supported without great injury a load of 620 000 lb., or 31 times the safe pressure for which the plates were designed. Any injured pieces could easily be replaced in order to maintain the efficiency of the cushion.

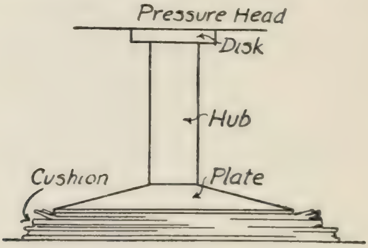


FIG. 7

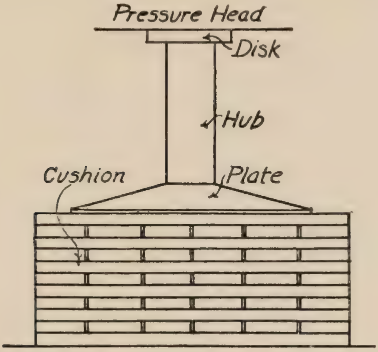


FIG. 8

Pressure was applied to the flat top of the plate by a hollow cylindrical cast-iron hub 12 inches long, 4 inches external diameter, and ¾ inch thickness of metal. Since the plates were not planed on top (which is seldom done in practical construction), several thicknesses of heavy manila paper were inserted between the hub and the plate. On the hub rested the pressure head of the testing machine, while the elastic cushion was placed between the plate and the bed of the machine. Thus the conditions of the test fairly represented those existing in actual structures, where the masonry yields somewhat and is not absolutely rigid like the bed of the testing machine.

The square steel plates were $^{13}/_{16}$ in. thick; the octagonal and circular steel plates were ¾ in. thick. The upward deflections of their outer edges were measured at 4 points to $^{1}/_{1000}$ in., and each plate was gradually loaded to 120 000 lb., or with six times its maximum safe load. This produced an average maximum deflection of 0.29 in., leaving a permanent set averaging 0.18 in., when the pressure was removed. The plate was thus dished, but no failure or cracks were produced.

These results show that a steel base plate bends more than one of cast iron, and that it does not so uniformly distribute its load over the masonry beneath it as a more inflexible cast-iron plate. It follows that the latter plate is preferable for the purpose. Empirical rules usually make steel plates one-half the thickness of cast-iron plates supporting equal loads.

Mr. Dick deduced from his experiments the following conclusions for steel plates.

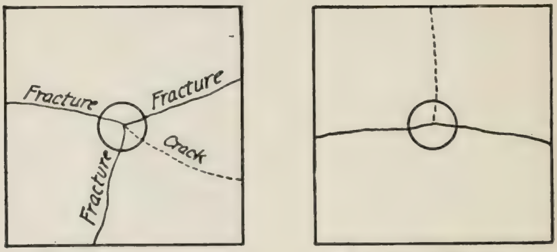
"1. The (preceding) formulas for the design of steel base plates are entirely safe.

2. The limit of 16 000 pounds fiber stress permitted by the Chicago ordinance is perhaps too large, since marked deflections take place rapidly after this fiber stress has been exceeded.

3. Steel plates projecting more than two diameters of the hub (or column) beyond it, should be designed for deflection, or it would be better to use a cast-iron plate for large loads.

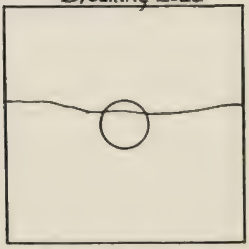
4. The circular is the most economical shape for a bearing plate."

The cast-iron plates were beveled on top from the hub to a uniform thickness of ⅜ in. at the edges, the bottom being a plane surface. They were cast and tested in sets of threes of each form. The square plates (Fig. 9) were $2^9/_{16}$ inches thick beneath the hub; the octagonal plates (Fig. 10) were 2⅛ inches, while the circular plates (Fig. 11) were $2^3/_{16}$ inches. All cast-iron plates were tested to fracture, which occurred with the load indicated in the figures for each plate. Plates *A* 1, *B* 1 and *C* 1 were tested on the cushion of folded blankets, etc. (Fig. 7), which crushed and distributed the pressure unequally, the plate thus failing under a smaller load. The other plates were tested on the wooden cushion, Fig. 8.



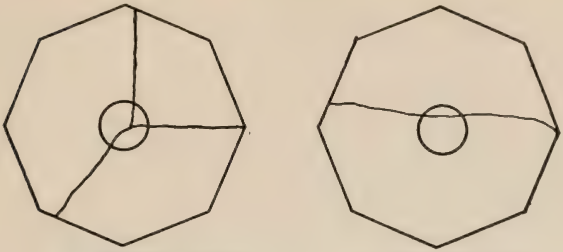
A1. Folded Cushion. 155000 lbs. A2. Wood Cushion. 268000 lbs.

Breaking Load



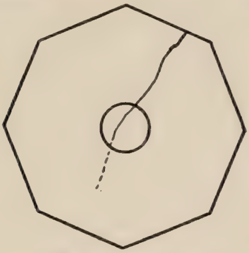
A3. Wood Cushion. 213500 lbs.

FIG. 9



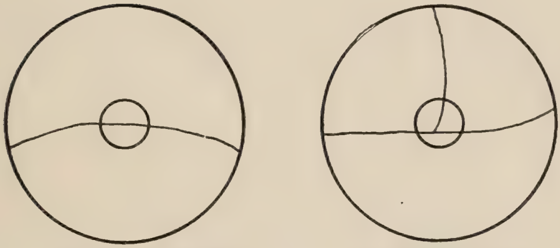
C1. Folded Cushion
67000 lbs.

C2. Wood Cushion
121000 lbs.



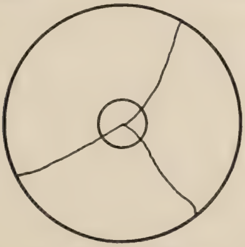
C3. Wood Cushion.
117500 lbs.

FIG. 10



B1. Folded Cushion
139000 lbs.

B2. Wood Cushion
275000 lbs.



B3. Wood Cushion
275500 lbs.

FIG. 11

From the results of these tests, Mr. Dick deduced the following conclusions for cast-iron plates.

"1. The (preceding) formulas for the design of cast-iron plates may be used with safety.

2. A greater fiber stress than that permitted by the Chicago ordinance could be used with safety.

3. Cast iron is better adapted for base plates than steel, as it gives a uniform distribution of the load over the bearing area for a greater range of loading.

4. Cast iron will not deteriorate as rapidly as steel when in a damp place, and for this reason cast iron should be preferred."

Mr. Dick likewise notes that the fracture lines pass through the center of each plate and are not tangent to the hub, as assumed by the preceding formulas. He also suggests that assuming the fracture line through the center of each plate, the resultant moment of the pressures about this line may be found and equated to the resistance moment of the fracture section. But since this procedure would render the formulas much more complex and increase the labor of designing a plate, the extra labor would not be repaid, being unnecessary for safety.

The direction of the fracture line in the plates tested was sometimes changed by the influence of side cracks, probably due to slight irregularities in the distribution of the pressure, or perhaps to slight flaws in the castings.

VI. New Formulas

The new formulas proposed are based on the following principles, the result of a theoretical investigation and of the nature of the failures of the plates.

1. The line of fracture is a shorter diameter of the plate.

2. The breaking moment about this line is greater than that about a line tangent to the column or hub.

3. The weight of a base plate is very small in proportion to the load transmitted by it, and it may safely be neglected in the formulas.

4. The pressures at the top and the bottom of the plate are then equal and act in opposed directions with unequal lever arms.

5. Their moments about the fracture line being necessarily unequal, their resultant maximum safe moment is equal to the maximum safe resisting moment of the fracture section of the plate.

VII. Resultant Bending Moment Acting About Fracture Line

Let A = total area of the plate in square inches;
P = total load in pounds transmitted by it;
L' = perpendicular distance in inches from fracture line to center of upward pressures on one-half the area of the plate;
then $L' = 0.25 \times$ length in inches of a wall or bearing plate;
$= 0.25 \times$ side of a square plate;
$= 0.2187 \times$ inscribed diameter of octagonal plate;
$= 0.2122 \times$ diameter of circular plate.
Let L'' = perpendicular distance in inches from fracture line to center of downward pressures on one-half the area of the plate;
then $L'' = 0.25 \times$ width of a beam or girder on a bearing plate;
$= 0.25 \times$ side of a solid square post or column;
$= 0.2187 \times$ diameter of solid octagonal post or column;
$= 0.2122 \times$ diameter of solid cylindrical post or column.
Let R = radius of outer circle inscribed in cross section of hollow square or cylindrical column;
r = radius of inner circle inscribed in hollow square or round column;

Then $L'' = 0.500 \dfrac{R^3 - r^3}{R^2 - r^2}$, for a hollow square column.

$$\text{Limiting values are} \begin{cases} 0.500R \text{ for a solid column.} \\ 0.750R \text{ for a very thin shell column.} \end{cases}$$

Also $L'' = .424 \dfrac{R^3 - r^3}{R^2 - r^2}$, for a hollow cylindrical column.

$$\text{Limiting values are} \begin{cases} .424R \text{ for a solid column.} \\ .637R \text{ for a very thin shell column.} \end{cases}$$

These values of L'' may readily be found by calculation, but much more easily by the aid of the graphical table, Fig. 12.

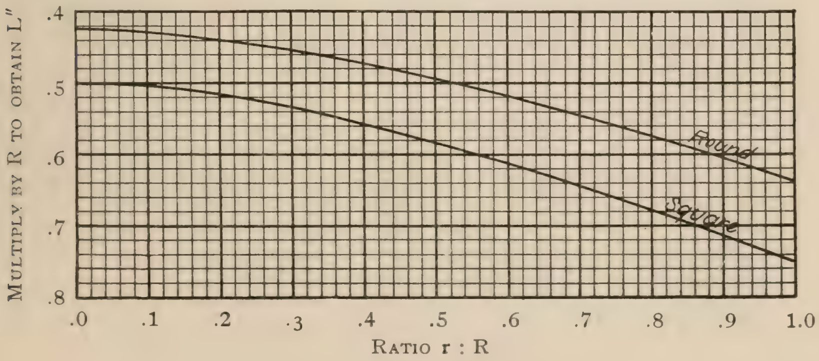


Fig. 12

Example. Assume a hollow cylindrical column, 12 in. external and 9 in. internal diameter.

Then $$\frac{r}{R} = \frac{4.5}{6.00} = 0.75.$$

By the table, Fig. 12, $L'' = 0.56\,R = 3.36$ in.

VIII. Resistance Moment of Fracture Section

The fracture section is a plane vertical section through the fracture line.

Let f = maximum safe fiber stress in pounds per square inch.
B = length in inches of fracture section.
t = thickness in inches of plate at center under column.
I = moment of inertia of the fracture section.
c = vertical distance in inches from horizontal neutral axis to bottom of fracture section.

Then $\dfrac{fI}{c}$ = maximum safe resistance moment of fracture section in general.

(*a*) For a rectangular fracture section of plate of uniform thickness,

$$\frac{fBt^2}{6} = \text{maximum safe resistance moment.}$$

(*b*) For tapered section with sharp edges. (Fig. 13.)

Let k = length in inches of horizontal top of section under column or diameter of column.

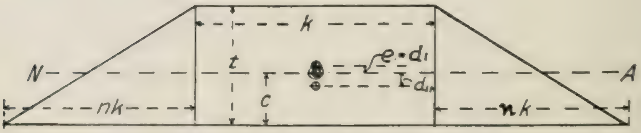


Fig. 13

nk = length in inches of each tapered portion of the fracture section.

$B = k(2n + 1)$ = length in inches of fracture section.

$A' = kt$ = area in square inches of rectangle in Fig. 13.

$A'' = nkt$ = area in square inches of both triangles in Fig. 13.

$d' = \dfrac{nt}{6(n+1)}$ = vertical distance in inches from center of gravity of rectangle to neutral axis of fracture section, Fig. 13.

$d'' = \dfrac{t}{6} - \dfrac{nt}{6(n+1)}$ = vertical distance from center of combined triangles to neutral axis of fracture section, Fig. 13.

$c = d'' + \dfrac{t}{3}$ = vertical distance in inches from neutral axis to bottom of fracture section.

Also $I = \dfrac{kt^3}{12} + ktd'^2$ = moment of inertia for rectangle.

$I = \dfrac{nkt^3}{18} + nktd''^2$ = moment of inertia for combined triangles.

Finally $\dfrac{fI}{c} = \dfrac{fk}{c}\left[\dfrac{t^3}{12} + td'^2 + \dfrac{nt^3}{18} + ntd''^2\right]$ = safe moment of resistance of fracture section of the plate. (7)

(*c*) For tapered section with thick edges (Fig. 14)

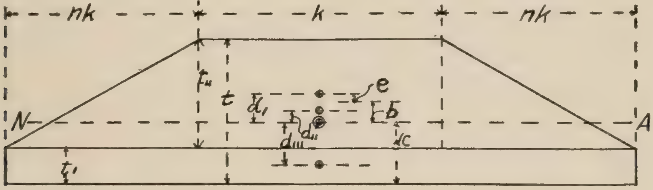


FIG. 14

Divide the fracture section into two rectangles and two triangles as in the figure.

Let t = thickness in inches at the middle of the plate.

t' = thickness in inches at the edges.

$t'' = t - t'$ = thickness of the taper in plate.

Then $A' = kt''$ = area in square inches of the upper rectangle.

$A'' = nkt''$ = area in square inches of combined triangles.

$A''' = (2n + 1)\ kt'$ = area in square inches of lower rectangle.

$e = \dfrac{nt''}{6(n+1)}$ = vertical distance in inches from center of gravity of upper rectangle to joint center of gravity of this rectangle and combined triangles.

$b = (\dfrac{t}{2} - e)\dfrac{A'''}{A' + A'' + A'''}$

$= (\dfrac{t}{2} - e)\left[\dfrac{(2n+1)t'}{t'' + nt'' + (2n+1)t'}\right]$ = vertical distance in inches from the preceding joint center of gravity to the neutral axis of fracture section.

Then $d' = e + b$ = vertical distance in inches from center of gravity of upper rectangle to neutral axis of fracture section.

$d'' = d' + \dfrac{t''}{6}$ = vertical distance from center of gravity of combined upper rectangle and both triangles to neutral axis of fracture section.

$d''' = \dfrac{t}{2} - d'$ = vertical distance in inches from center of gravity of lower rectangle to neutral axis of section.

Then $I' = \dfrac{kt''^3}{12} + kt''d'^2$ = moment of inertia of upper rectangle about the neutral axis.

$I'' = \dfrac{nkt''^3}{18} + nkt''d''^2$ = moment of inertia of combined triangles about the neutral axis.

$I''' = \dfrac{(2n+1)}{12}kt'^3 + (2n+1)\ kt'd'''^2$ = moment of inertia of lower rectangle about the neutral axis.

Finally, summing these results for moment of inertia of entire section:

$$\frac{fI}{c} = \frac{fk}{c}\left[\frac{t''^3}{12} + td'^2 + \frac{nt''^3}{18} + nt''d''^2 + \frac{(2n+1)t'^3}{12} + (2n+1)\ t'd'''^2\right], =$$

resistance moment of fracture section of a plate with thick edges $= t'$. (8)

IX. METHOD OF APPROXIMATION

As cast-iron plates are generally made with thick edges, the practical application of the last formula is quite tedious. In order to apply it, it becomes necessary first to assume the thicknesses t, t' and t'', then using the preceding formulas to determine the corresponding safe resistance moment of the fracture section. This process must doubtless be repeated several times before a plate is found which has the required safe moment of resistance of section. Hence the necessity for a simplification of the method by directly obtaining the required values of the thicknesses t, t' and t'', which is accomplished in the following manner.

By the formula for a rectangular fracture section, the values of

$$\frac{I}{c} = \frac{bt^2}{6} = \frac{kt^2}{6}(2n + 1) \tag{9}$$

are computed for $n = 0$, $n = 1$, $n = 2$, $n = 3$, $n = 4$, $n = 5$, and these values lie in a straight line, when they are plotted as in the uppermost line in Fig. 15.

By formula (7) for tapered plates with sharp edges, are next computed the values of $\frac{I}{c}$ corresponding to $n = 0$, $n = 1$, $n = 2$, $n = 3$, $n = 4$, and $n = 5$. These values are then plotted in Fig. 15, forming the slightly curved and dotted line, next to the lower straight line. Joining the ends of the curve by the straight full line, this is found to almost coincide with the curved line, for which it may be substituted with a slight error on the safe side.

Similarly for $n = 5$ only, $\frac{I}{c}$ is computed for edge thickness $t' = 0.1\,t$, $0.2\,t$, $0.3\,t$, $0.4\,t$, $0.5\,t$, $0.6\,t$, $0.7\,t$, $0.8\,t$, and $0.9\,t$. These values are laid off on the vertical for $n = 5$, and straight radial lines are drawn to these points in Fig. 15. The corresponding per cents of resistance may then be easily computed for $n = 5$, as written in Fig. 15, and which signify that the resistance moment of a tapered fracture section is a certain per cent of that of a rectangular section of equal thickness, only for $n = 5$.

It now remains to determine this per cent for any other value of n.

The graphical table in Fig. 16 is readily computed and plotted from the data obtained in Fig. 15. It is used as follows:

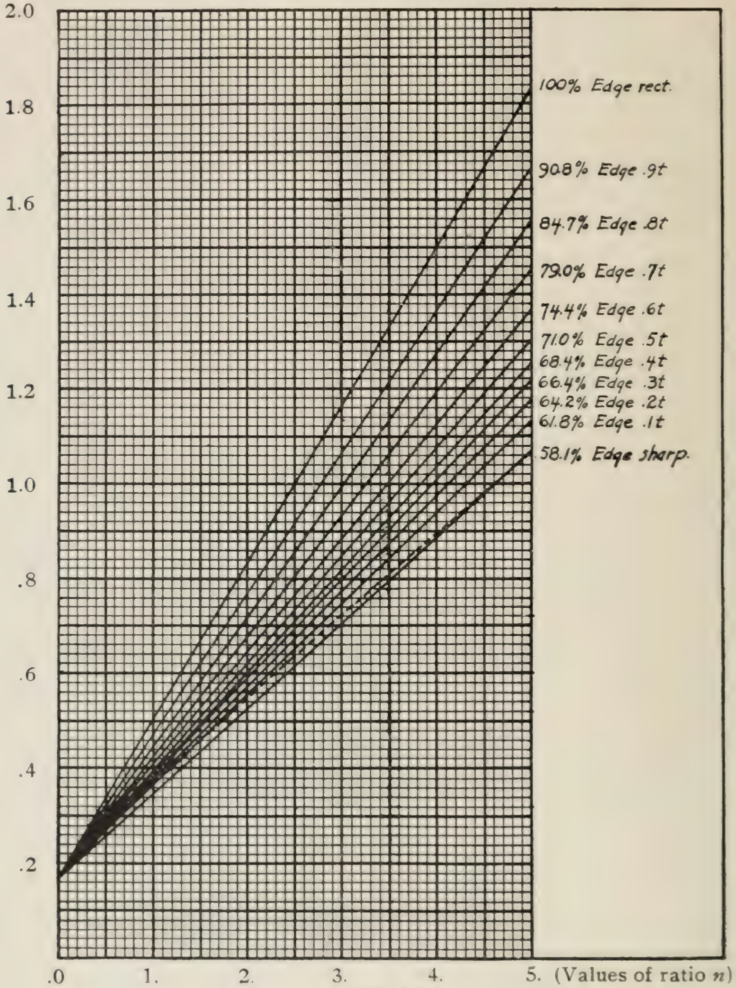


FIG. 15

Let @ = per cent of resistance moment of a rectangular fracture section, which is possessed by a tapered section with the same thickness t and the same value of n.

Example 1. Let $t' = 0.3\ t$ = edge thickness and $n = 2$.

A vertical through 2 in Fig. 16 intersects the curve 0.3 on a horizontal through 70.5 at the left, which is the required per cent.

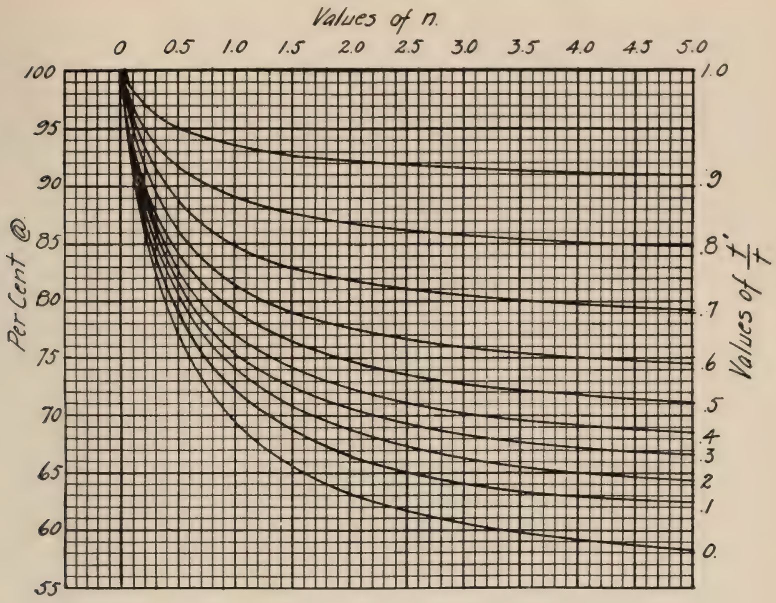


Fig. 16

Example 2. Let $t' = 2.5$ and $n = 3.5$.

A vertical through 3.5 intersects the interpolated curve 2.5 on a horizontal through 70.2 at the left, the required per cent.

It is further evident that the actual thickness t of a tapered plate must be somewhat greater than that of a plate of uniform thickness, when both are required to possess equal resistance moments.

The general formula for base plates is:

$$t = \sqrt{\frac{3\,P}{fB}(\,L' - L''\,)} =$$

thickness in inches for a plate of uniform thickness. (10)

Or
$$t = \frac{1}{50}\sqrt{\frac{3\,P}{B}(\,L' - L''\,)} =$$

thickness for a cast-iron plate. (11)

Let @ = per cent corresponding to $\frac{t'}{t}$ and n, found by table (Fig. 16)

Then for cast iron, $t = \sqrt{\frac{100}{@}}\,\frac{1}{50}\sqrt{\frac{3\,P}{B}(\,L' - L''\,)}$ = required thickness t under the column for a tapered cast-iron plate, possessing a resistance moment equal to that of a plate of uniform thickness t determined by formula 11. (12)

X. COMPLETE FORMULAS FOR PLATES OF UNIFORM THICKNESS

By equating the resultant bending and safe resistant moments acting about the neutral axis of the fracture section of the plate, the following general formulas are obtained:

The primary formula is:

$$M = \frac{P}{2}(L' - L'') = R = \frac{fI}{c}. \tag{13}$$

(*a*) Bearing plate on wall (Fig. 17)

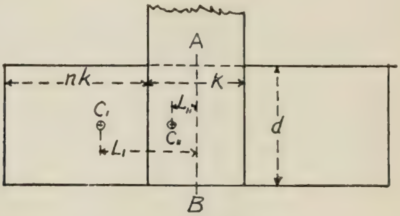


FIG. 17

Let d = width in inches of the plate, usually equal to the thickness of the wall.

Then

$$\frac{P}{2}(L' - L'') = \frac{fdt^2}{6}.$$

Or

$$\frac{Pnk}{4} = \frac{fdt^2}{6}.$$

Hence $t = \sqrt{\frac{3\,Pnk}{2\,fd}}$ = thickness of the plate in inches. (14)

And $t = \frac{1}{103.3}\sqrt{\frac{Pnk}{d}}$ = thickness in inches of a steel plate. (15)

$t = \frac{1}{44.7}\sqrt{\frac{Pnk}{d}}$ = thickness of cast-iron plate, $f = 3000$ lb. (16)

$t = \frac{1}{40.8}\sqrt{\frac{Pnk}{d}}$ = thickness of cast-iron plate, $f = 2500$ lb. (17)

If a square or cylindrical column stands on the bearing plate instead of the end of a beam resting thereon, L'' is to be found and then inserted in the general formula, by which t may then be found. (Sec. VII). The general formulas then become:

$$t = \frac{1}{103.3}\sqrt{\frac{P}{d}\left(\frac{nk}{2}+\frac{k}{4}-L''\right)} =$$

thickness for steel plate. (18)

$$t = \frac{1}{44.7}\sqrt{\frac{P}{d}\left(\frac{nk}{2}+\frac{k}{4}-L''\right)} =$$

thickness for cast-iron, $f = 3000$ lb. (19)

$$t = \frac{1}{40.8}\sqrt{\frac{P}{d}\left(\frac{nk}{2}+\frac{k}{4}-L''\right)} =$$

thickness for cast-iron, $f = 2500$ lb. (20)

Formulas 16, 17, 19 and 20 are also applicable to cast-iron bearing plates tapered in thickness from beam or column to each end, since the fracture section always remains rectangular in form.

(*b*) Square plate (Fig. 18)

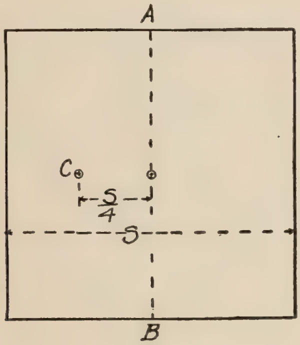


FIG. 18

Let $S =$ side of square plate in inches.

Then $t = \sqrt{\frac{3\,P}{fS}\left(\frac{S}{4} - L''\right)} =$ thickness of plate in inches. (21)

$$t = \frac{1}{73}\sqrt{\frac{P}{S}\left(\frac{S}{4} - L''\right)} =$$

thickness of steel plate in inches. (22)

$$t = \frac{1}{31.6}\sqrt{\frac{P}{S}\left(\frac{S}{4} - L''\right)} =$$

thickness for cast-iron, $f = 3000$ lb. (23)

$$t = \frac{1}{28.9}\sqrt{\frac{P}{S}\left(\frac{S}{4} - L''\right)} =$$

thickness for cast-iron, $f = 2500$ lb. (24)

(*c*) Octagonal plate (Fig. 19)

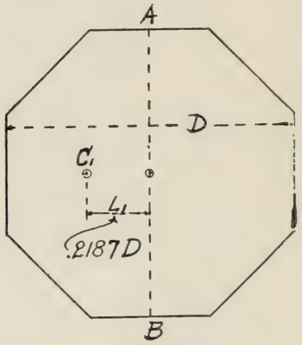


FIG. 19

Let D = inscribed diameter of octagon.

$L' = .2187D$.

$$t = \sqrt{\frac{3\,P}{fD}\left(.2187D - L''\right)} =$$

thickness of plate in inches. (25)

$$t = \frac{1}{73}\sqrt{\frac{P}{D}\left(.2187D - L''\right)} =$$

thickness of steel plate. (26)

$$t = \frac{1}{31.6}\sqrt{\frac{P}{D}\left(.2187D - L''\right)} =$$

thickness of cast-iron plate, f =3000 lb. (27)

$$t = \frac{1}{28.9}\sqrt{\frac{P}{D}\left(.2187D - L''\right)} =$$

thickness of cast-iron plate, $f = 2500$ lb. (28)

(*d*) Circular plate (Fig. 20)

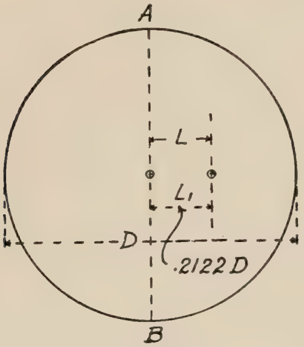


FIG. 20

Let D = diameter of the plate in inches.

$L' = .2122D$.

$$t = \sqrt{\frac{3\ P}{fD}\left(.2122D - L''\right)} =$$

thickness of the plate. (29)

$$t = \frac{1}{73}\sqrt{\frac{P}{D}\left(.2122D - L''\right)} =$$

thickness for steel plate. (30)

$$t = \frac{1}{31.6}\sqrt{\frac{P}{D}\left(.2122D - L''\right)} =$$

thickness for cast-iron, $f = 3000$ lb. (31)

$$= \frac{1}{28.9}\sqrt{\frac{P}{D}\left(.2122D - L''\right)} =$$

thickness for cast-iron, $f = 2500$ lb. (32)

XI. For Plates of Tapered Thickness

These comprise all cast-iron base plates, which are always made thinner at their edges for the sake of economy. Bearing plates of cast iron set on walls, however, have a rectangular fracture section, for which direct formulas have already been given. (Formulas 16, 17, 19, 20.)

The thickness required at the middle of a tapered cast-iron plate may now be easily found.

1. Compute the thickness for a rectangular fracture section.
2. Assume the desired ratio $\frac{t'}{t}$ of thickness at edge and middle.
3. By the table, Fig. 16, determine the per cent @ of its resistance in comparison with a plate of rectangular section of equal width and thickness.
4. By formula 12 compute the required actual thickness t at the middle of the plate. Then t' is easily found.

Example. A hollow cylindrical cast-iron column has an external diameter of 6 in., is ¾-in. thick and transmits a load of 60 000 lb. to the plate. Required the safe dimensions of a square cast-iron base-plate; fiber stress 2500 lb. per sq. in.; ratio $\frac{t'}{t} = 0.15$.; safe resistance of masonry under plate = 125 lb. per sq. in.

$$\sqrt{\frac{60\,000}{125}} = 21.91 \text{ in.} = \text{side of plate required.}$$

$$nk = \frac{21.91 - 6.}{2} = 7.96\,; \quad n = \frac{7.96}{6.00} = 1.33.$$

For this column, $R = 3.00$, $r = 2.25$; $\frac{r}{R} = 0.75$.

By the table, Fig. 12, $L'' = 0.56$, $R = 1.68$ in.

By formula 24,

$$t = \frac{1}{28.9}\sqrt{\frac{60\,000}{21.91}\left(\frac{21.91}{4} - 1.68\right)} = 3.53 \text{ in.}$$

By the table, Fig. 16, for $\frac{t'}{t} = 0.15$ and $n = 1.33$, @ = 71 per cent.

By formula 12,

$$t = \sqrt{\frac{100}{71}} \times 3.53 = 4.19 \text{ in.} = \text{the required middle thickness.}$$

And 4.19 × 0.15 = 0.63 in. = thickness at the edge of the plate.

XII. Graphical Tables

It is evident from the example just worked out, that the calculations required for any particular base plate are quite simple and rapid, particularly if 4-place logarithms are employed. It is, however, entirely possible to devise a series of graphical tables for materially reducing this labor, thus saving valuable time and lessening liability to errors.

XIII. Table for Dimensions of Base Plates

Fig. 21 is a graphical table for determining by inspection the side of a square, or the diameter of an octagonal or round plate, required to safely transmit loads not exceeding 200 tons (400 000 lb.), allowing safe pressures of the plate on masonry between 50 and 250 lb. per sq. in. Fig. 22 is merely an enlarged portion of the same table for loads not exceeding 20 tons.

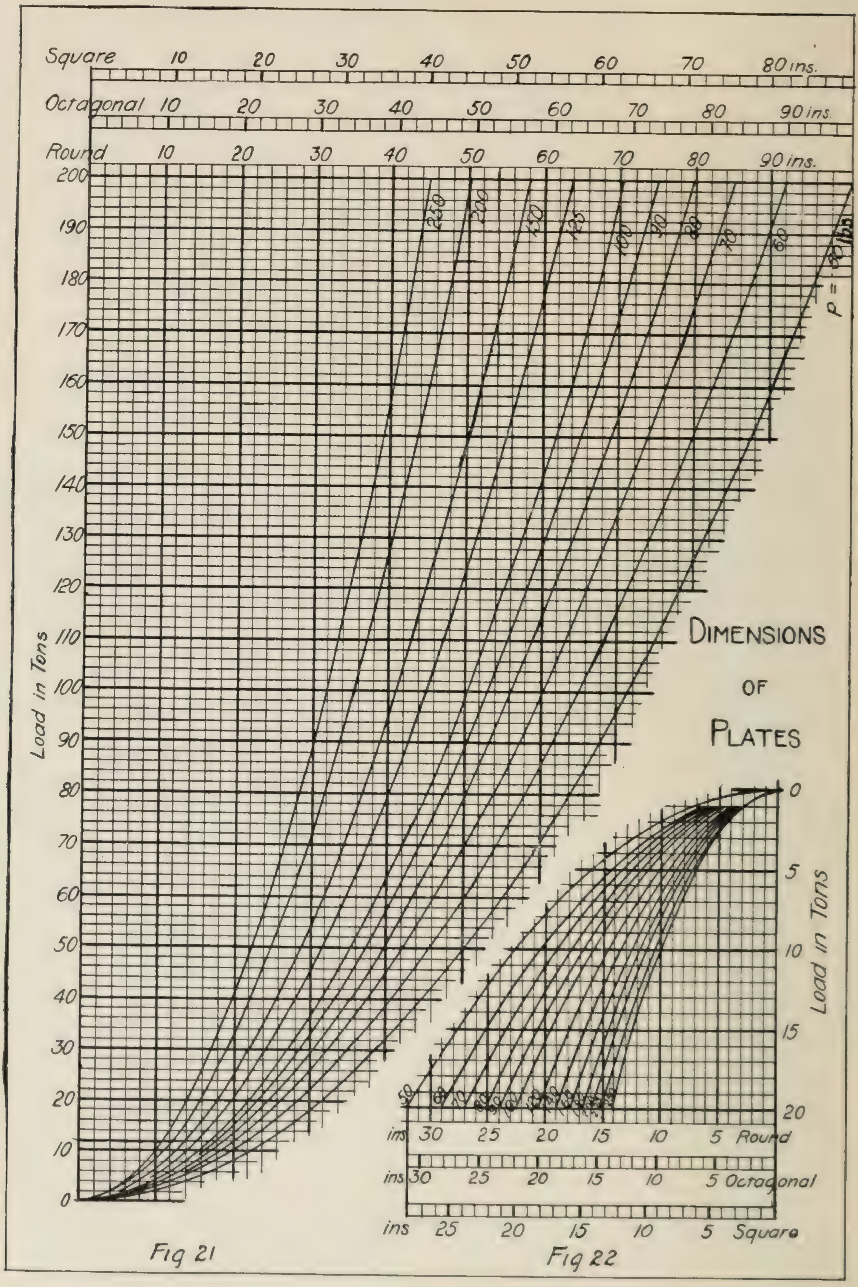
By the use of the upper scale corresponding to the shape of the plate, it is possible to employ this single table for square, octagonal and circular plates, by reading the required side or diameter on the proper scale.

Example. A plate is required to safely transmit a load of 100 tons, allowing a safe pressure of 125 lb. per sq. in. on the masonry beneath it.

Locating the intersection of a horizontal through 100 tons with the curve for 125 lb., and following a vertical through this point to the respective scales at the top of the table, we read the following values:

40.0 in. = side of a square plate required.
42.0 in. = diameter of an octagonal plate.
45.0 in. = diameter of a circular plate.

Pressures intermediate between the given curves can be easily located with sufficient accuracy.



DIMENSIONS OF PLATES

Fig 21

Fig 22

XIV. TABLE FOR THE FACTOR $\sqrt{\frac{3P}{B}}$

The general formula for a plate of uniform thickness is

$$t = \sqrt{\frac{3P}{fB}}\,(L' - L'') = \text{thickness in inches.} \qquad (10)$$

This may be factored in the form

$$t = \sqrt{\frac{3P}{B}} \times \sqrt{\frac{L' - L''}{f}} = \text{thickness in inches.}$$

Fig. 23 exhibits the relations of the three quantities

P = total load in tons transmitted by the plate.

B = length in inches of the fracture section.

$\sqrt{\frac{3P}{B}}$ = one factor in the last formula.

Example. Take the square plate in the last example. $P = 100$ tons, $B = 40.0$ in. The intersection of a horizontal through 100 tons with the curve for 40.0 in., and a vertical through this point gives at the top of the table $\sqrt{\frac{3P}{B}} = 122.5$.

Assume that a 12-in. cylindrical cast-iron column with 1¼-in. metal stands on this base plate.

Then $\frac{r}{R} = \frac{4.75}{6.00} = 0.79$, and by the table in Fig. 12:

$$L'' = .572 \times 6.00 = 3.43 \text{ in.}; \; L' = \frac{40}{4} = 10.0 \text{ in.}$$

Hence $L' - L'' = 10.0 - 3.43 = 6.57$ in.

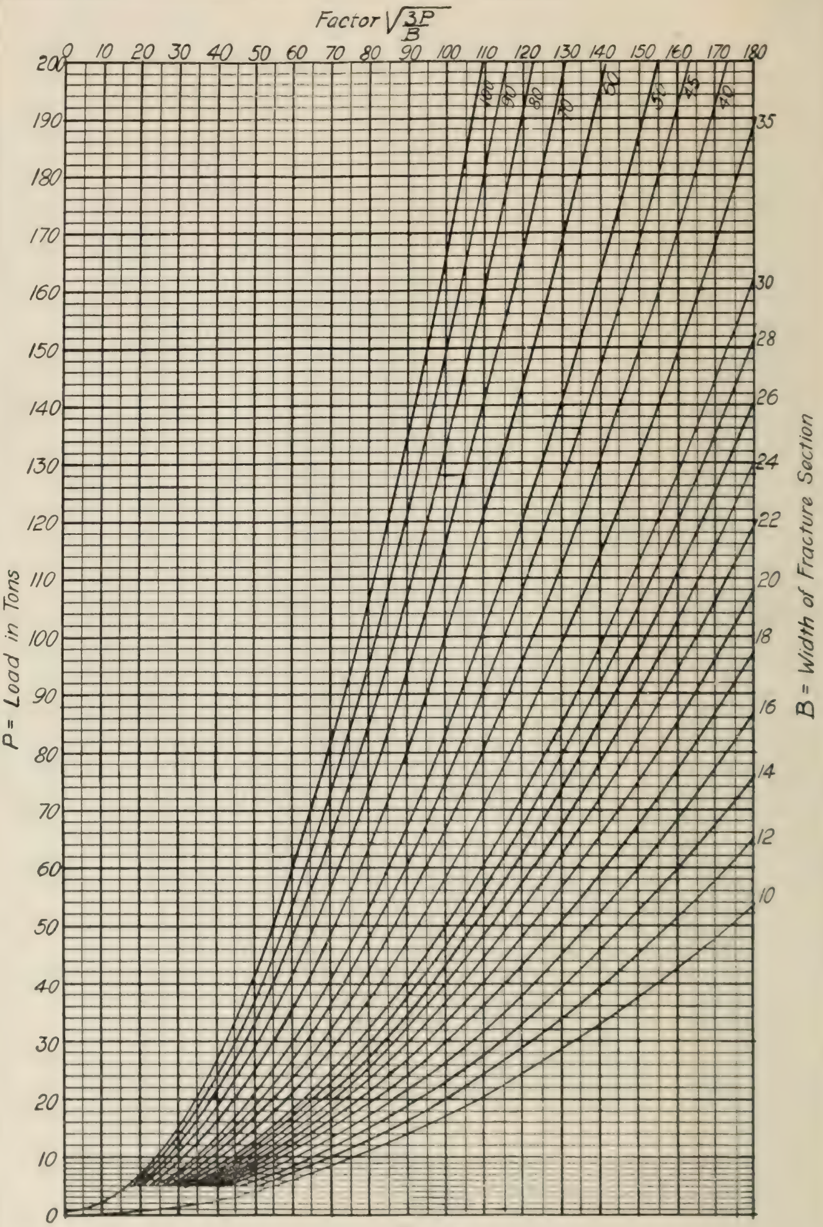

Factor $\sqrt{\frac{3P}{B}}$
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
P = Load in Tons
100
90
80
70
60
50
45
40
35
30
28
26
24
22
20
18
16
14
12
10
B = Width of Fracture Section

Fig. 23

XV. TABLES FOR PLATES OF UNIFORM THICKNESS

The table in Fig. 24 exhibits the relations of the three quantities:

$\sqrt{\frac{3P}{B}}$ = the factor whose value has just been found from Fig. 23.

$L' - L''$ = difference in lever arms of the upward and downward bending moments.

t = thickness in inches represented by curved lines in the table.

In designing the tables in Fig. 24 and 25, the factor $\sqrt{\frac{L' - L''}{f}}$ is actually employed, but the device of separate vertical scales for the different values of f makes the table more convenient for use.

Resuming the last example and employing the table Fig. 24, a vertical through 122.5 at the top intersects a horizontal through 6.57 at the left, giving by estimation between the nearest curves the following values for t.

$t = 2\frac{1}{2}$ in. for a steel plate.
$t = 2\frac{13}{16}$ in. for a wrought-iron plate.

Employing the table, Fig. 25, in the same manner for cast-iron plate of uniform thickness:

$t = 5\frac{3}{4}$ in. for fiber stress of 3000 lb. per sq. in.
$t = 6\frac{5}{16}$ in. for fiber stress of 2500 lb. per sq. in.

Assuming 0.20 for the ratio $\frac{t'}{t}$, and $n = 1.17$, by the table, Fig. 16, @ = 72.5 per cent.

By formula 12,

$$t = \sqrt{\frac{100}{72.5}} \times 5.75 = 6.76 \text{ in. at middle for } f = 3000 \text{ lb. per sq. in.}$$

$$t = \sqrt{\frac{100}{72.5}} \times 6.31 = 7.41 \text{ in. at middle for } f = 2500 \text{ lb. per sq. in.}$$

Then $6.76 \times 0.2 = 1.35$ in., and $7.41 \times 0.2 = 1.48$ in., the respective thicknesses at the edges required.

It will be seen that Fig. 24 contains two vertical scales, one for steel with fiber stress of 16 000 lb. per sq. in. and the other for wrought iron with fiber stress of 12 000 lb. per sq. in. Fig. 25 likewise has two vertical scales corresponding to fiber stresses of 3000 lb. and 2500 lb. per sq. in.

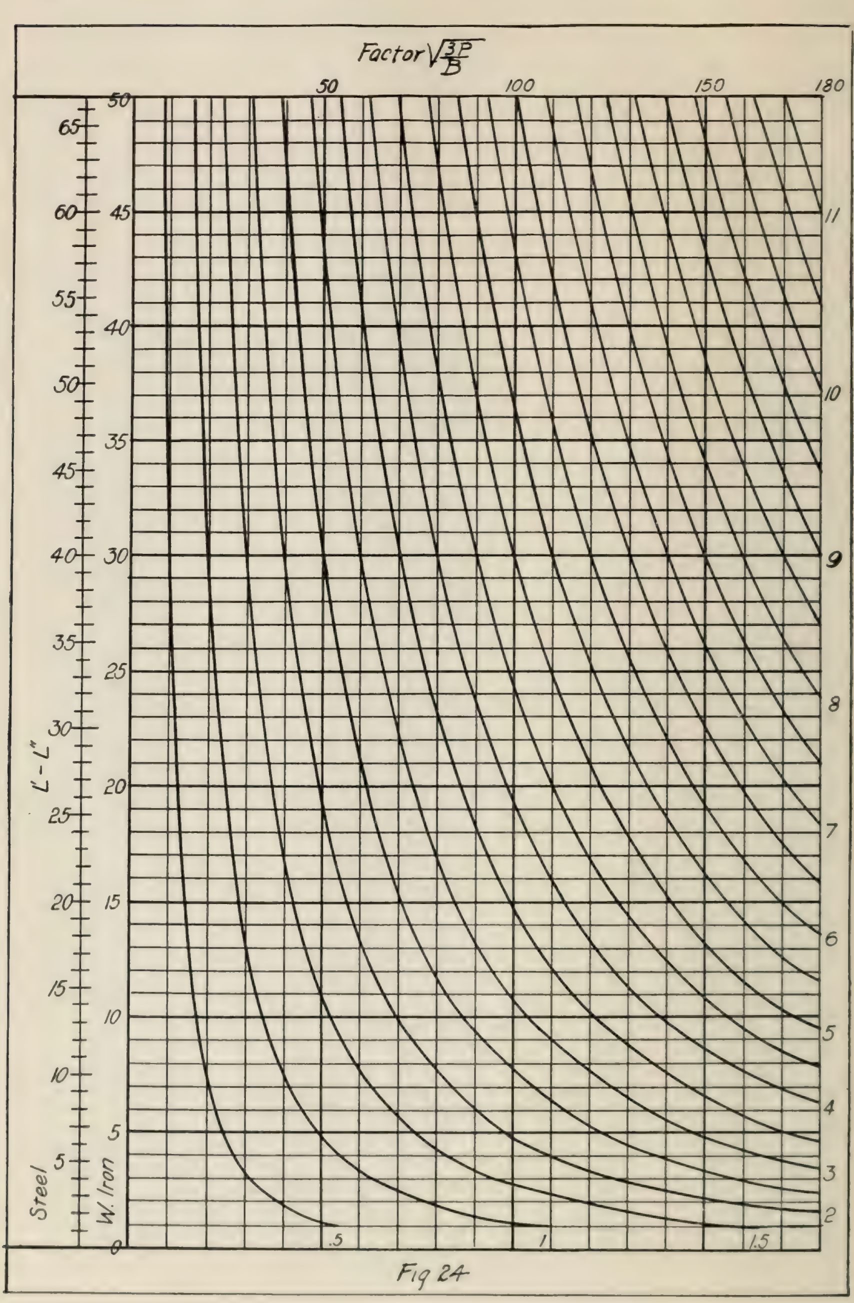

Factor $\sqrt{\frac{3P}{B}}$
50
100
150
180
L' - L"
Steel
65
60
55
50
45
40
35
30
25
20
15
10
5
W. Iron
50
45
40
35
30
25
20
15
10
5
0
11
10
9
8
7
6
5
4
3
2
.5
1
1.5

Fig 24

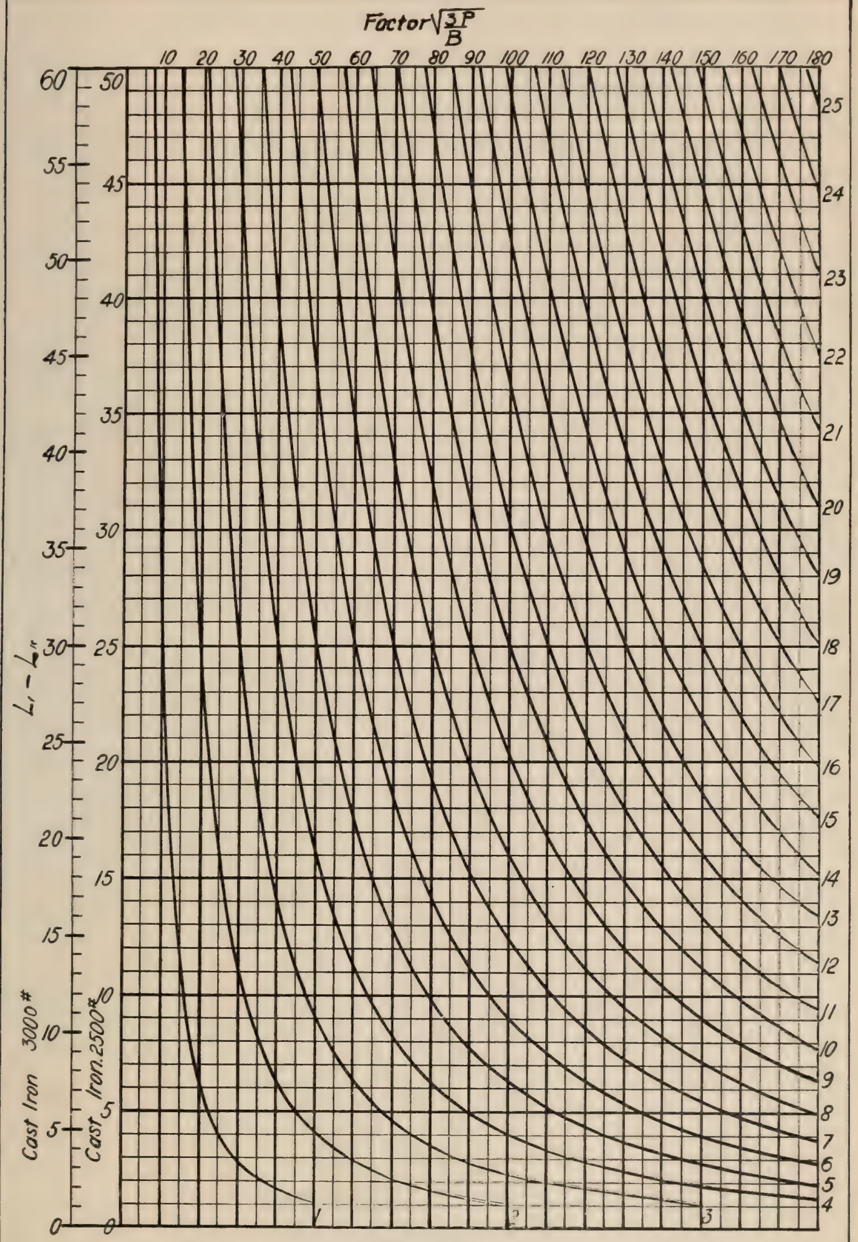

Factor √(3P/B)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
60
55
50
45
40
35
30
25
20
15
10
5
0
50
45
40
35
30
25
20
15
10
5
0
L₁ - L₂"
Cast Iron 3000#
Cast Iron 2500#
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
1
2
3

Fig 25

XVI. Additional Examples of the Use of the Tables

1. A bearing plate is 12 in. wide and rests on a 13-in. wall; it supports a load of 15 tons (30 000 lb.) transmitted by the end of a girder 12 in. wide. Safe pressure of plate on masonry = 100 lb. per sq. in. Safe fiber stress for cast iron = 2500 lb. per sq. in. Required its thickness.

$$\frac{15 \times 2000}{100 \times 12} = 25.0 \text{ in.} = \text{length of the plate,}$$

$$nk = \frac{25 - 12}{2} = 6.5 \text{ in.} = \text{projection of end beyond side of girder;}$$

By formula 17,

$$t = \frac{1}{40.8}\sqrt{\frac{Pnk}{d}} = \frac{1}{40.8}\sqrt{\frac{30\,000 \times 6.5}{12.0}} =$$

3.12 in., the thickness beneath the girder. The plate may be tapered from the girder to any desired thickness at its ends without danger, since its fracture section is always rectangular.

If the safe fiber stress be taken = 3000 lb. per sq. in.;

$$t = \frac{40.8 \times 3.12}{44.7} = 2.85 \text{ in., say, } 2\tfrac{7}{8} \text{ in.}$$

Or by the table, Fig. 21, a plate 17.25 in. square would be required.

Hence, length $\frac{(17.25)^2}{12} = 25.0$ in., as before.

Also by the table, Fig. 23, the factor $\sqrt{\frac{3P}{B}} = 86.0$.

$$L' = \frac{25.0}{4} = 6.25\ ;\ L'' = \frac{12.0}{4} = 3.00\ ;$$

$$L' - L'' = 6.25 - 3.00 = 3.25 \text{ in.}$$

By the table, Fig. 25, $t = 3\tfrac{1}{8}$ in. as before.

Therefore, the graphical tables may also be used for bearing and wall plates.

2. A square base plate transmits a load of 50 tons to masonry with a safe resistance of 150 lb. per sq. in. Safe fiber stress 3000 lb. per sq. in. A column 7 in. external diameter and 1 in. thickness of metal stands on this plate.

By the table, Fig. 21, 22.7 in. = side of plate, and $n = 1.12$.

By the table, Fig. 23, $\sqrt{\frac{3P}{B}} = 114.5$.

$L' = 5.68$ in.; $L'' = 1.91$ in. by Fig. 12. $L' - L'' = 3.76$ in.

By the table, Fig. 25, $t = 3\,{}^5/_{16}$ in. = 3.31 in.

Assuming $\frac{t'}{t} = 0.25$, which is a commonly employed ratio, and $n = 1.12$, @ = 73.5 by the table in Fig. 16.

By formula 12,

$$t = \sqrt{\frac{100}{73.5}} \times 3.31 = 3.86 \text{ in.} = \text{thickness at middle, and}$$

$$t' = 3.86 \times 0.25 = 0.97 \text{ in. thickness at edges.}$$

3. A circular base plate transmits a load of 175 tons to masonry with a safe resistance of 175 lb. per sq. in. A column of metal 12 in. in diameter and 1¼ in. thick stands on this plate.

By the table, Fig. 21, 50.5 in. = diameter of the plate; $n = 1.60$.

By the table, Fig. 23, $\sqrt{\frac{3P}{B}} = 144$. Also $L' - L'' = 7.29$ in.

By the table, Fig. 24, $t = 3.10$ in. for a steel plate.
$t = 3.50$ in. for a wrought-iron plate.

By the table, Fig. 25, $t = 7.05$ in. for cast-iron plate, $f = 3000$ lb. per sq. in.
$t = 7.75$ in. for cast-iron plate, $f = 2500$ lb. per sq. in.

Assuming
$\frac{t'}{t} = 0.25$, and as $n = 1.60$, by the table, Fig. 16, @ = 71.0.

Then

$$t = 7.05 \times \sqrt{\frac{100}{71}} = 8.37 \text{ in.} = \text{thickness beneath column}, f = 3000 \text{ lb.}$$

$$t = 7.75 \times \sqrt{\frac{100}{71}} = 9.20 \text{ in.} = \text{same, for } f = 2500 \text{ lb.}$$

Therefore

$t' = 2.09$ in. in the first case and 2.30 in. in the second.

4. Assume that in the last case the plate is to be square and that the safe resistance of the masonry is but 90 lb. per sq. in.

In the same manner as before, we easily find:

Side of plate = 62.2 in.; $n = 2.09$.

$$\text{Factor } \sqrt{\frac{3\,P}{B}} = 130$$

$t = 3\frac{5}{8}$ in. for a steel plate
$t = 4\frac{3}{4}$ in. for a wrought-iron plate
$t = 8\frac{3}{8}$ in. for cast-iron plate, $f = 3000$ lb.
$t = 9\frac{1}{8}$ in. for same with $f = 2500$ lb.

Assuming $\frac{t'}{t} = 0.25$, and for $n = 2.09$; @ = 69.5.

Then $t = 10.00$ in. thickness at middle in the first case and $= 10.95$ in the second. The corresponding values for t' are 2.50 and 2.74 inches.

5. A built steel column is composed of two 15-in. channels, one 15-in. I, and two 16 x $\frac{3}{4}$-in. plates. It stands on a circular cast-iron base plate, which rests directly on a cylindrical sunken foundation pier of portland cement concrete, to which the plate transmits a load of 500 tons (1 000 000 lb.) Maximum safe fiber stress in cast iron is taken at 2500 lb. per sq. in. Safe resistance of the concrete pier is 175 lb. per sq. in. Let $\frac{t'}{t} = 0.20$.

Required least safe diameter and thickness of the cast-iron plate.

In this case, $\frac{1\,000\,000}{175} = 5714.3$ sq. in., area of plate.

$$d = \sqrt{\frac{5714}{.7854}} = 85.3 \text{ in.} = \text{diameter of the plate}; \; n = 2.17.$$

By formula Sec. VII, $L' = 85.3 \times 0.2122 = 18.1$ in.

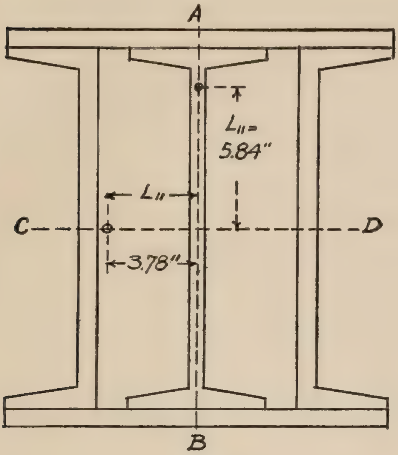


FIG. 26

For the given cross section of the steel column, Fig. 26, there may readily be found by the usual graphical methods:

$L'' = 5.84$ in. about the axis CD.

$L'' = 3.78$ in. about the axis AB.

Taking the smaller of these values and applying formula 32,

$$t = \frac{1}{28.9}\sqrt{\frac{P}{B}(L' - L'')} = \frac{1}{28.9} \times$$

$$\sqrt{\frac{1\,000\,000}{85.3}(18.10 - 3.78)} = 14.18 \text{ in.}$$

Assuming $\frac{t'}{t} = 0.20$, and for $n = 2.17$, by table in Fig. 16,

$$@ = 68.0$$

Then $t = \sqrt{\frac{100}{68.0}} \times 14.18 = 17.20$ in. = thickness under column, and $t' = 17.2 \times 0.20 = 3.44$ in. = thickness at edge of plate.

Such a solid plate would be more simple and more easily set in place, and it might also be cheaper than the usual arrangement consisting of a cast-iron ribbed base plate or stool above a layer of short steel 15-inch I-beams, which are set on the top of the concrete pier. This pier would also here require to be not less than 8 ft. 6 in. in diameter at the top.

These examples show that simple formulas and tables have been here devised, making the calculation of safe plain bearing and base plates a very simple matter.

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THE THERMAL CONDUCTIVITY OF FIRE-CLAY AT HIGH TEMPERATURES

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I. INTRODUCTION[1]

The problem of thermal conductivity has for a long time furnished a favorite field of research for the physicist.[2] In reviewing the investigations of the past, many experiments, forming gradual approaches to a solution of this problem, will be found on record.[3] Nearly all of these experiments, however, were made at temperatures between that of melting ice, and steam at atmospheric pressure, and in no instances were even moderately high temperatures reached.[4] These experiments show that the chief difficulties have been the obtaining and maintaining of a high temperature, the determination of the quantity of heat conducted through the material, and the measurement of the correct temperature gradient in the specimen under test. Fortunately for present-day investigations, the electric heating coil and the thermocouple enable us to solve these problems with comparative ease and with a high degree of accuracy.

Although the investigation described in this bulletin was undertaken in the attempt to solve a specific problem,—the thermal conductivity of fire-clay at high temperatures,—the method developed will no doubt be of interest in other lines of work where the question of thermal conductivity is of importance. For instance, in all problems of refrigeration, this is a factor of the greatest importance. In the construction of cold storage buildings, a convenient method for testing the various building materials would be of great value, although, of course, working at low temperatures would present a somewhat different problem.[1]

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[1] The investigation described in this bulletin was conducted in the Physical Laboratory of the University of Illinois by W. L. Egy, a research fellow of the Engineering Experiment Station. Its inception is due to Dr. J. K. Clement, and to him also is due the credit for the selection of the general method. Dr. A. P. Carman, Professor of Physics, advised Mr. Egy concerning the later phases of the investigation.

[2] See "The Conductivity, Porosity and Gas Permeability of Refractory Materials," by S. Wolagdine and A. L. Queneau, in Electro-Chemical and Metallurgical Industry, Sept., 1909, p. 383; Oct., 1909, p. 433. It is a singular coincidence that after many years in which no work was done upon this subject, two attempts should be made independently and practically at the same time.

[3] E. H. Hall, Phys. Rev., Vol. X, p. 277. June, 1900. Holborn & Wien, Zeitsch. Ver. Deutsch. Ingen., Vol. 40, 1896. Lees & Chorlton, Phil. Mag., Vol. 41, p. 495, Sec. 5, 1896. G. Glage, Ann. d. Physik., Vol. 323, p. 904, Dec., 1905. C. Niven, Roy. Soc. Proc., Vol. 76 A, p. 34, April 22, 1905. Tait, Trans. Roy. Soc. Edin., Vol. 28, p. 717, 1879.

[4] An account has recently been published of some very excellent work done by Dr. Wilhelm Nusselt on the "Thermal Conductivity of Heat Insulators." Some of his measurements were made at temperatures as high as 550° C. See Engineering, Vol. 87, pp. 1, 2, Jan. 1, 1909.

The primary object of these investigations in determining the thermal conductivity of fire-clay was to obtain information concerning the loss of heat through the walls of boiler furnaces. It is a well-known fact that considerable heat escapes through the walls of furnaces, but no idea of the amount of this heat has heretofore been obtained by direct methods. Nor do we have any definite knowledge of the effect of this heat, which passes through the walls, upon the different materials of which they are composed. While the engineer knows that the thicker the wall, the less heat is lost, he does not know how far he will be justified in increasing the thickness of the wall, until he has secured accurate data of the quantity of heat lost in this way.

To illustrate,—knowing the thermal conductivity, K, of brick, the dimensions of the furnace, and the inside and outside temperatures of the walls, the quantity of heat transmitted through them may readily be calculated. Taking the specific case of a 210 H. P. Heine boiler at the University of Illinois, when working under full load,—the area of walls exposed to the hot gases is about 364 sq. ft., and the thickness of the same about 20 in. The average temperature of the inside of this area is approximately 1400° F., and of the outside, 150°F. If we now take the value of K as found for that test-piece which was nearest like the brick in the setting, that is, $K = .0026$, (See Curve No. 2), and calculate the heat conducted through the walls we have, using *c. g. s.* units,

$$Q = .0026 \; \frac{.555\ (1400-150)}{2.54\ (20)} \; 929\,(364) \times 3600$$

(See formula 1, page 4.)

$$Q = 43{,}400{,}000 \text{ calories per hour}$$
$$\text{or } 172{,}000 \text{ B. t. u. per hour}$$

This is about 1.6 per cent of the total heat generated. These figures are only approximations, but they show that with careful measurements, the heat lost through the various parts of the walls may be calculated directly.

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[1] The conductivity of the substances in the earth's crust is of interest to geologists. The British Association for the Advancement of Science had a committee working for seven years to determine the conductivity of some of the rocks in the British Isles. (Herschel, Lebour, and Dunn, Rep. Brit. Assn., Vol. 49, 1879.)

II. PRINCIPLES OF THERMAL CONDUCTIVITY

A brief resumé of the principles of thermal conductivity follows:

The quantity of heat, Q', flowing through a given wall is proportional to the difference in temperature, $T_1 - T_2$, of the two faces. For a given difference in temperature, Q' is inversely proportional to the thickness, r. The heat flowing through a section of the wall will, of course, be proportional to the area, A, of that section. Q' is necessarily proportional also to the time, t, over which measurements are taken. Using these principles,

$$Q' = K \frac{T_1 - T_2}{r} At \qquad \text{..........................(1)}$$

K is a constant for the given substance at any temperature, and is called the internal thermal conductivity or simply the thermal conductivity of that material. If Q is expressed in calories; $T_1 - T_2$ in centigrade degrees; A, in square centimeters; r, in centimeters; and t, in seconds, K will be in *c. g. s.* units.

If we consider a lamina of infinitesimal thickness, dr, the difference in temperature between its faces being dT, for a time, dt,

$$Q' = K \frac{T - (T + dT)}{dr} Adt = -KA \frac{dT}{dr} dt \qquad \text{......(2)}$$

The expression $\frac{dT}{dr}$ is called the temperature gradient at the point in question, or in other words, the change in temperature per unit thickness.

From equation (2) $K = -\frac{Q}{A} \frac{dr}{dT}$ ....(3)

where Q is the heat flowing across the area A in unit time.

From the above expression, it may be seen that in order to determine the thermal conductivity of a substance, it is necessary to measure the quantity of heat flowing through a unit area, and the temperature gradient. The most accurate method of measuring Q, is to generate a known quantity of heat by means of an electric heating circuit, in such a manner that all the heat generated must flow through the substance to be tested. If a constant quantity of heat is generated until conditions have reached an equilibrium, then the quantity of heat conducted through the material per second must be equal to the quantity generated per second. This method may be used with a heating coil either in a hollow sphere or in a long cylinder. The latter form was chosen for these tests because of the experimental difficulties arising in the former.

In using this method, the assumption is made that there will be no escape of the heat longitudinally at the middle of the cylinder; that is, the exact amount of heat generated by a centimeter length of the coil, taken at the middle, must flow out through the corresponding circular section of just one centimeter thickness. To avoid errors from this cause, the length of the cylinder must be several times greater than its diameter.

The test-pieces were made into cylinders about 40 cm. in length and 12 cm. in diameter, with a hole through the center about 3.5 cm. in diameter for the reception of the heating coil. Four longitudinal holes about 3 mm. in diameter were made, in which thermocouples could be placed for the measurement of the temperature.

Applying equation 3 to the case of a cylinder, the heat, Q, generated by 1 cm. length of the coil in unit time is expressed by

$$Q = \frac{.2394 \quad EI}{l} \quad \text{calories}$$

where E represents volts, I, amperes, and l, the length of the coil in centimeters. The constant, .2394, is the reciprocal of the mechanical equivalent of a calorie expressed in joules or watts. The area perpendicular to the flow of heat at a distance r from the axis is $2\pi r$ per unit length. Substituting for Q and A in equation 3

$$K = - \frac{.2394 \quad EI}{2\pi lr} \cdot \frac{dr}{dT} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Assuming that K is constant between the temperatures T_1 and T_2 and integrating

$$K = \frac{.2394}{2\pi l} \cdot \frac{EI}{T_1 - T_2} \log \; (r_2/r_1) \ldots\ldots\ldots (5)$$

where T_1 and T_2 are the temperatures at points distant r_1 and r_2, respectively, from the axis. For any given values of r_1 and r_2, the only variables in this equation are EI, the electrical watts dissipated in the coil, and $T_1—T_2$, the difference in temperature between r_1 and r_2. Thus our expression may be reduced to

$$K = C \frac{EI}{T_1 - T_2} \qquad \ldots\ldots\ldots\ldots\ldots (6)$$

where $$C = \frac{.2394 \log (r_2/r_1)}{2\pi l}$$

III. DESCRIPTION OF THE APPARATUS

Cylinders.—The cylinders tested were made by the Laclede-Christy Clay Products Company, St. Louis, Missouri. Twelve test-pieces were obtained, made up from four different mixtures, which were marked *A*, *B*, *1* and *3*.

Those marked *A* were of a dark reddish-brown color and contained no gravel. The structure appeared similar to sandstone. After heating in the test, these pieces were cracked in a great many places. The pieces marked *B* were also of a reddish-brown color, but were of medium coarse structure. They contained very small pieces of white gravel throughout the mass. Those marked *1* were a little coarser than the *B* cylinders and were brown in color. They contained a very small amount of gravel. Cylinders *3* were almost white and very coarse. They contained a large amount of gravel.

One cylinder of each composition was tested at temperatures ranging from 400° C. to 800° C. or 900° C. The remaining pieces were tested at only one temperature. One of the cylinders, marked *1*, could not be tested because the holes in it for the insertion of the thermocouples were not deep enough.

Furnace.—Fig. 2 shows a longitudinal section of the furnace ready for use. *aa* is the test-piece. This was surrounded by a larger cylinder, *bb*, of fire-clay, in order to get uniform radiation from *aa*, and also to maintain higher temperatures. Coverings, *cc*, were placed over each end to prevent loss of heat in this direction. The whole was supported by an open framework of strap iron. A thermocouple was placed in each of the holes, *D* and *F*.

Heating Coil.—The heating coil was made of pure nickel wire about 1.8 mm. in diameter, wound nine turns to the inch upon a ½-in. porcelain electric insulator tube. Commercial insulator tubes 20 in. long were taken for this purpose and the enlarged end cut off, leaving

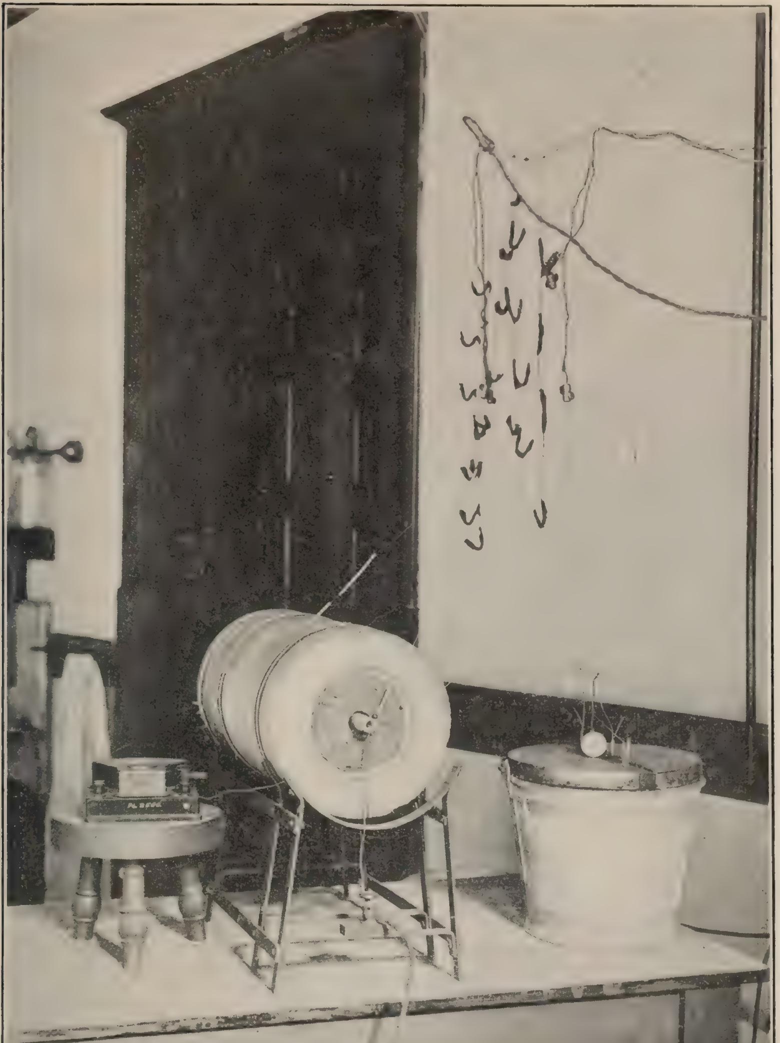


FIG. 1 TEST-PIECE SURROUNDED BY FIRE-CLAY JACKET—ALSO SHOWING THERMOCOUPLES IN PLACE

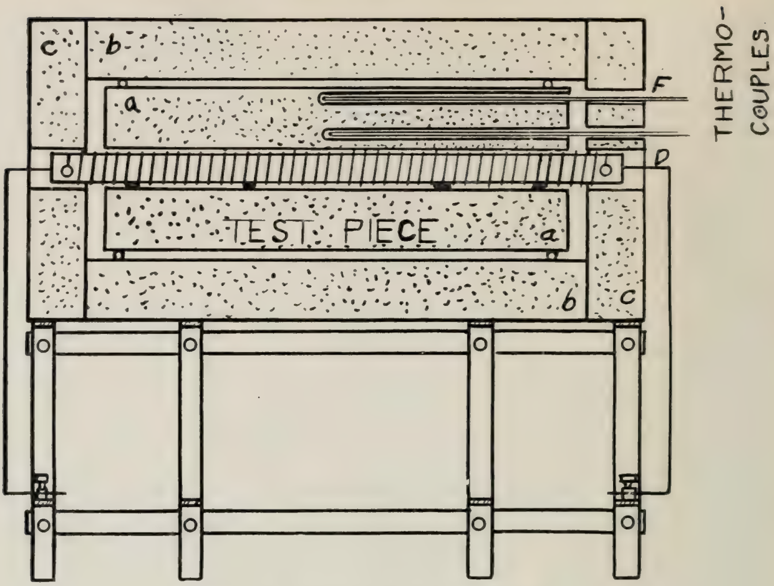


FIG. 2 SECTION OF FURNACE

them 18 or 19 in. long. Small holes were chipped in the ends of each tube, and the ends of the wire pulled tightly through these holes, thus holding the wire in place. The holes were 16⅛ in. apart, allowing 145 turns of wire, or an equivalent length of 40.9 cm. Potential leads were fastened to the power wire where it emerged from the insulator, by winding one end of a piece of smaller wire tightly about it. The place where this connection was made had a rather high temperature, so nickel was used to prevent any thermo-electric effect at the junction.

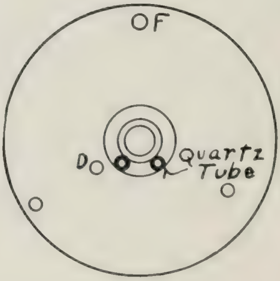


FIG. 3

The coil was at first supported in the cylinder by two small pieces of quartz tubing at each end (see Fig. 3). At the higher temperatures, however, the insulator softened and sagged down in the middle, and two additional pieces of quartz were placed under it, each one-third the distance from either end. The holes in the end of the furnace were packed with asbestos to prevent the escape of heat. The heating coil was made a few turns longer than the test-piece to prevent cooling of the ends.

IV. Method of Measurements

The current was measured by a Weston direct-reading portable standard millivoltmeter and shunt. The current was taken from 110-volt mains and was regulated by means of two large rheostats, as in the calibration work, (Appendix). As it was necessary to maintain the current constant to one-tenth of an ampere for several hours at a time, and the line voltage varied considerably, a storage battery was placed across the mains as shown in Fig. 4. By means of another resistance, the current from the mains was adjusted to a few amperes less than that flowing through the furnace. In this way only a few amperes were drawn from the battery and its voltage remained constant through a considerable change of the line voltage. This was not always sufficient, however, for satisfactory operation.

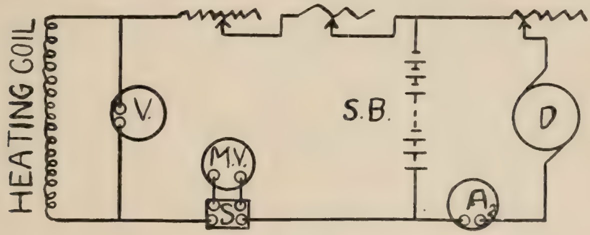


Fig. 4

The voltage drop through the coil was measured by a Weston portable voltmeter, the smallest division of which corresponded to one volt. The temperature coefficient of nickel is very large, and the resistance of the wire varied considerably with the temperature. As the turns at the end of the coil were somewhat cooler than those in the middle, their resistance was less, and the average voltage drop per centimeter for the whole coil would be less than the drop per centimeter of the central portion. As the average value was used in the calculations, an error would thus be introduced. This was compensated for, by having the potential leads connected to the heating circuit, as stated above, outside the insulator, thus adding to the potential drop across the actual 145 turns, the drop in the wire from the last turn to the point of connection.

The temperatures were measured by platinum—platinum-rhodium thermocouples, made by Heraus. in Germany, and calibrated by the melting-point method described in the Appendix. The couples were also calibrated in opposition as a differential couple. This was done by placing both couples in a quartz tube in a large piece of iron and heating the iron up to about 1100° C., taking the reading of the differential couple at various temperatures. The couples were placed in the small holes (D, F, Fig. 2) in the test-piece far enough so that the junctions were midway between the ends. The two wires were insulated from each other by placing very small porcelain tubing over the platinum-rhodium wire.

The electromotive force of the couples was measured by a Wolff potentiometer and a galvanometer, as in the calibration (See Appendix). Each couple was read separately and then the two were connected in opposition and read as a differential couple. The relation

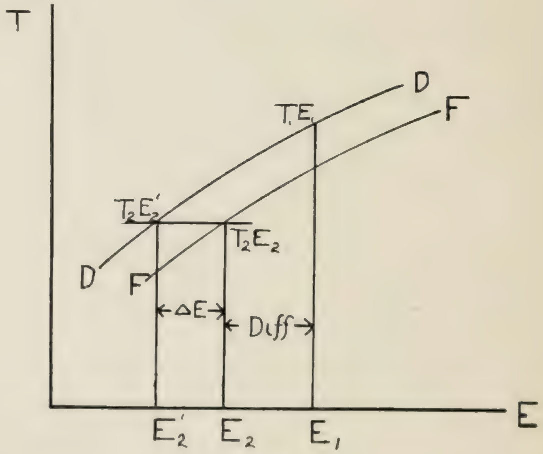


FIG. 5

between this reading and the corresponding difference in temperature is obtained as follows:

Let us call these readings Diff. Let the curve DD (Fig. 5) represent the relation between temperature and electromotive force for couple D, and curve FF, that for couple F. Let E_1 and E_2 be the readings of couples D and F, respectively. The curve DD is expressed by the equation,

$$T_1 = A + BE_1 + CE_1^2$$

and

$$T_2 = A + BE'_2 + C\,(E'_2)^2$$

then

$$T_1 - T_2 = B\,(E_1 - E'_2) + C[E_1^2 - (E'_2)^2]$$

now

$$E'_2 = E_2 - \triangle E$$

and $E_1 = E_2 + \text{Diff.}$ ("Diff" is the reading of the differential). Substituting for E_1 and E'_2 above,

$$T_1 - T_2 = B\,(\text{Diff} + \triangle E) + C\,(\text{Diff} + \triangle E)\ \ (E_1 + E_2 - \triangle\ E.$$

$\triangle E$ is negligible in comparison with $(E_1 + E_2)$ and may be dropped from the last factor.

Manipulation.—The arrangement of the potentiometer circuits is shown in Fig. 6. From the ice bath the couples were connected to two "single-pole double-throw" switches (1 and 2) which were mounted on the same base. Throwing switch No. 1 to the left and No. 2 to the right, couple D could be read. Reversing No. 2 placed F in the circuit. With both switches to the right, the two couples were connected in the circuit in opposition, in their proper order, since D was the hotter couple and therefore had the higher electromotive force.

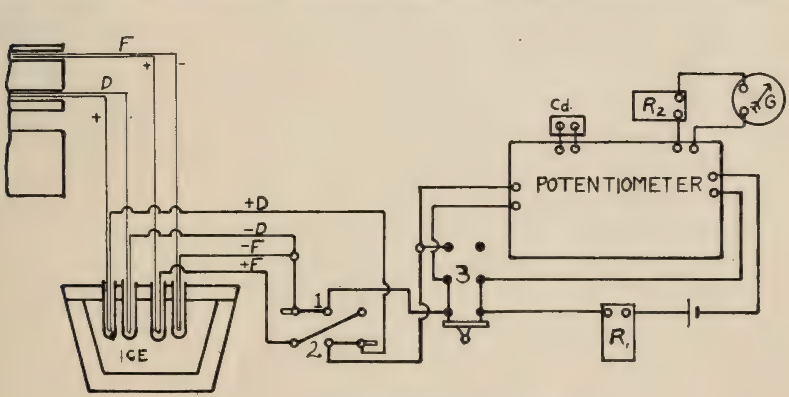


FIG. 6 POTENTIOMETER CIRCUIT

The statement was made above that the heat which was generated at the middle of the coil flowed out along radial lines. This was tested by moving the outer couple *F* (Fig. 2), back and forth in a longitudinal direction and noting the reading in the various positions. This operation showed that the temperature was constant to 0.3° C. for a distance of 6 or 7 cm. from the middle. As no heat will flow along constant temperature lines, there could be no longitudinal flow of heat in the 12 or 14 cm. in the middle of the test-piece, and hence the assumption is allowable.

The general method of operation was to start the furnace with a rather large current, about 25 amperes, and gradually reduce this. as the furnace approached the temperature desired. This took from three to five hours for the lower temperatures. The storage battery would then be placed in the circuit (see Fig. 4) and the current kept constant for two or three hours more. When the outer couple, *F*, showed a temperature constant to one-tenth of a degree, indicating equilibrium conditions, readings were taken. The voltage and current readings were taken before and after the temperature readings, in order to be sure there was no change. The temperature readings were taken in the order, *D*, *F*, *D*, (*D-F*), and *D*. It will be noticed by referring to Fig. 6, that only one change of either switch No. 1 or No. 2 is necessary to change from any one of the above readings to the next in order. Each cylinder, at the close of the tests on it, was broken across the middle, and r_1 and r_2 carefully measured in the plane in which the temperature readings had been taken.

V. RESULTS

Tables 1 to 4 show the readings and results obtained from the first four cylinders. The curves also show the values of the conductivity at the different temperatures. The tables give, in order. (from left to right), the voltage drop across the furnace *E;* the current flowing through the coil *I*; the reading of the inner couple (*D*); the outer couple *(F)*, and of the two connected in opposition as a differential couple *Diff.*, corrected as described above, in micro-volts; the temperature difference, $T_{\text{diff.}}$, calculated from the differential reading; the average temperature of the two couples and the conductivity, *K*. The readings are arranged in the order of increasing temperatures, although they were not taken in this order in every case. It will be noticed that the conductivity of the two coarser fire-clays was constant, while that of the other two which were of finer structure increased with the temperature.

Table 5 gives the comparative values of the different cylinders in the order in which they were tested. The particular value given for each of the first four was so chosen as to be near the temperature at which the later pieces of the same composition were tested.

The accuracy of the values for K in this work is limited to the accuracy in measuring r_1 and r_2. The temperature readings are certainly accurate to 1.0° C., and very probably to 0.5° C. The voltage and current readings are accurate to one per cent. An error may be introduced in the values of r_1 and r_2 because of the uncertainty of the position of the thermo-junction in the hole. If the couple were touching one side of the hole, it would take the temperature of that side, while r_1 and r_2 were always measured to the center of the holes. This error, however, would be a constant factor for the tests on any cylinder, since the couples were never disturbed after they were once placed in a cylinder, until the completion of the tests on that piece. Thus the comparative values of K for any given specimen at different temperatures would not be affected by the values of r_1 and r_2.

The greatest error is caused by changes of current through the furnace. The supply voltage changed a great deal, and the batteries used were not large enough to maintain the current constant at all times. If the current should change just before a reading was taken, the temperatures would not correspond to the other readings, though they might not be changing at the time. The variation between cylinders of the same composition is probably due to a difference in porosity. An investigation of the effect of porosity as well as composition of substances would, no doubt, lead to more definite results, in regard to a comparison of fire-clays.

TABLE 1

Mark	r_1	r_2	E	I	D	F	Diff	T_{diff}	$T_{ave.}$	K
B	23.5	58.0	27.6	15.4	3677	2067	1597	170.9	362.4	.00209
..	....	....	33.6	17.2	4595	2470	2116	223.9	430.6	.00217
..	....	....	35.2	17.8	5325	2990	2319	242.6	494.2	.00217
..	....	....	38.8	18.7	5928	3257	2657	276.1	537.8	.00221
..	....	....	40.9	19.1	6541	3634	2889	297.3	586.6	.00221

TABLE 2

Mark	r_1	r_2	E	I	D	F	Diff	T_{diff}	$T_{ave.}$	K
3	33.8	52.0	30.1	17.8	3700	2919	781	81.3	406.5	.00264
..	....	....	36.3	19.8	4687	3621	1066	108.4	493.2	.00266
..	....	....	36.0	19.8	4729	3667	1063	108.0	497.7	.00265
..	....	....	40.0	20.9	5423	4164	1261	126.0	557.5	.00266
..	....	....	40.9	21.1	5514	4232	1285	128.1	565.4	.00270
..	....	....	43.9	21.7	6023	4540	1485	146.3	605.7	.00261
..	....	....	46.3	22.0	6587	4991	1601	155.4	655.2	.00267
..	....	....	47.3	22.3	6626	4992	1635	158.6	657.1	.00263
..	....	....	50.6	22.5	7208	5402	1809	172.9	704.6	.00264

TABLE 3

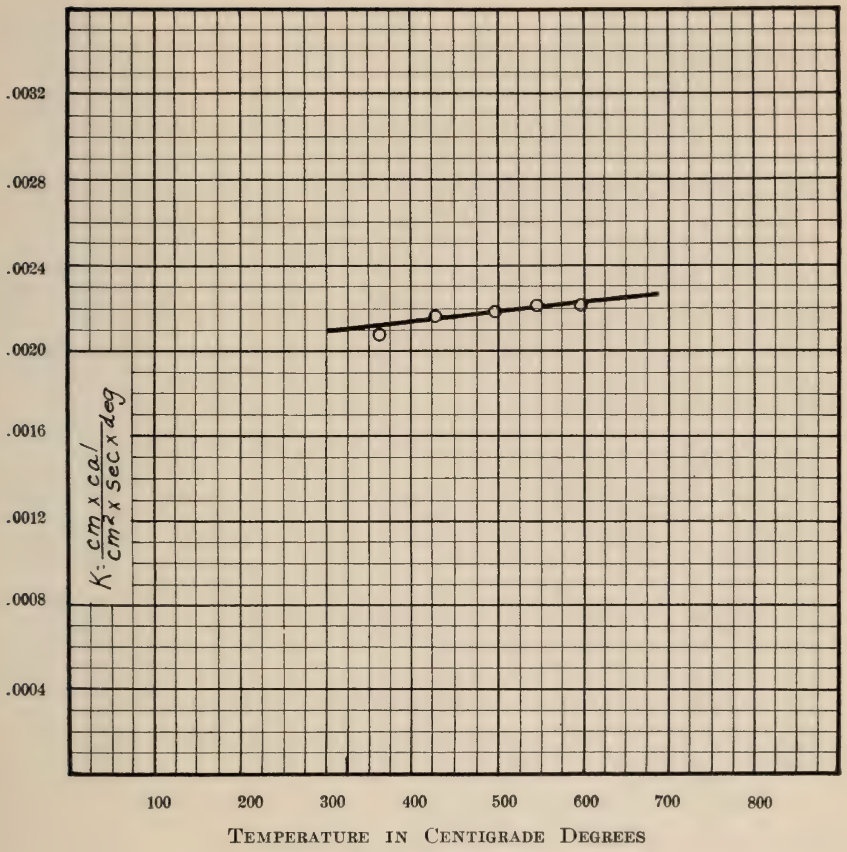
Mark	r_1	r_2	E	I	D	F	Diff	T_{diff}	$T_{ave.}$	K
A	33.3	66.0	39.2	19.9	5197	3190	2001	203.3	496.2	.00245
..	....	....	43.8	19.0	5827	3664	2164	216.4	551.6	.00245
..	....	....	45.5	20.7	6347	3958	2387	236.0	591.7	.00254
..	....	....	49.7	20.4	6924	4232	2693	263.0	633.0	.00246
..	....	....	51.7	20.3	7279	4480	2800	271.0	662.1	.00247
..	....	....	52.7	20.2	7301	4512	2795	270.4	664.7	.00251
..	....	....	52.8	20.5	7377	4598	2782	268.5	672.6	.00251
..	....	....	59.7	20.8	8337	5032	3305	312.4	738.0	.00252
..	....	....	61.0	21.0	8399	5069	3336	314.9	742.6	.00259
..	....	....	61.8	20.6	8591	5191	3403	319.7	757.2	.00254

TABLE 4

Mark	r_1	r_2	E	I	D	F	Diff	T_{diff}	$T_{ave.}$	K
1	23.9	49.3	29.6	16.8	3572	2697	876	91.6	388.2	.00366
..	....	....	34.8	18.4	4547	3386	1159	118.5	474.0	.00364
..	....	....	42.6	20.5	6031	4335	1678	165.7	596.7	.00355
..	....	....	45.2	21.2	6430	4583	1847	180.7	627.4	.00358
..	....	....	54.3	22.8	8085	5640	2449	230.2	756.5	.00362

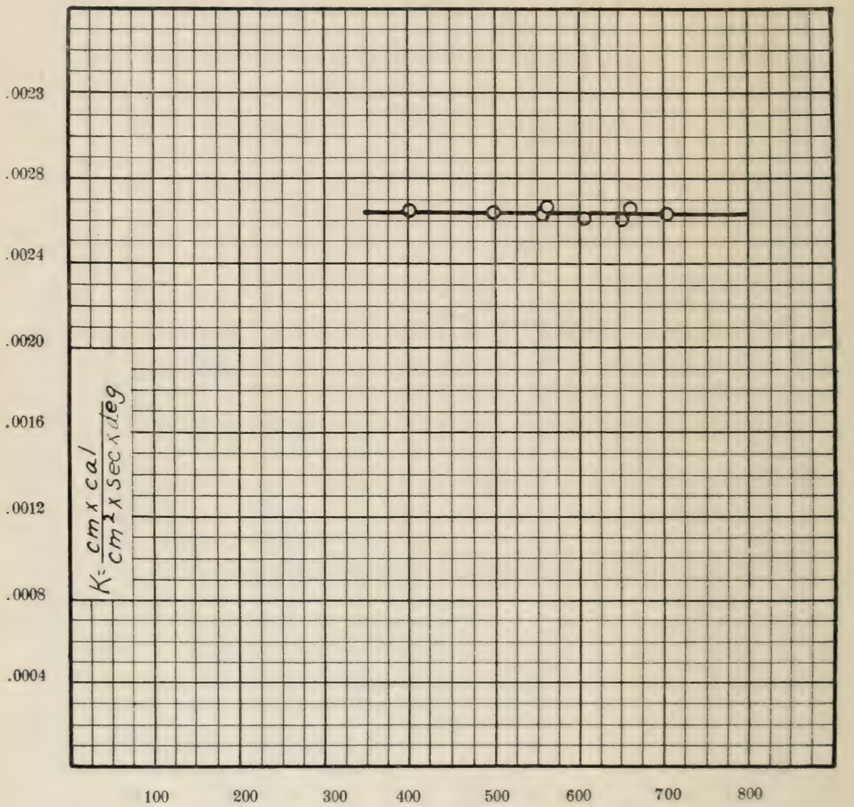
TABLE 5

	Mark	r_1	r_2	E	I	D	F	Diff	T_{diff}	$T_{ave.}$	K
1	B	23.5	58.0	40.9	19.1	6541	3634	2889	297.3	587	.00221
2	3	33.8	52.0	50.6	22.5	7208	5402	1809	172.9	705	.00264
3	A	33.3	66.0	52.7	20.2	7301	4512	2795	270.4	665	.00257
4	1	23.9	49.3	54.3	22.8	8085	5640	2449	230.2	757	.00362
5	3	31.0	48.4	42.0	20.5	5633	4429	1205	119.6	581	.00299
6	A	29.0	56.0	54.0	20.1	8170	5414	2756	259.6	749	.00256
7	3	27.0	49.5	57.0	19.7	8556	6001	2558	237.5	795	.00267
8	1	30.0	51.0	60.5	20.1	8318	5888	2433	227.1	770	.00265
9	B	32.0	51.5	63.0	19.0	8823	6716	2210	202.1	891	.00263
10	B	27.5	46.0	44.0	20.3	6535	4638	1900	185.5	635	.00231
11	A	26.5	61.5	45.0	20.1	7483	4623	2860	275.4	679	.00257



Curve No. 1

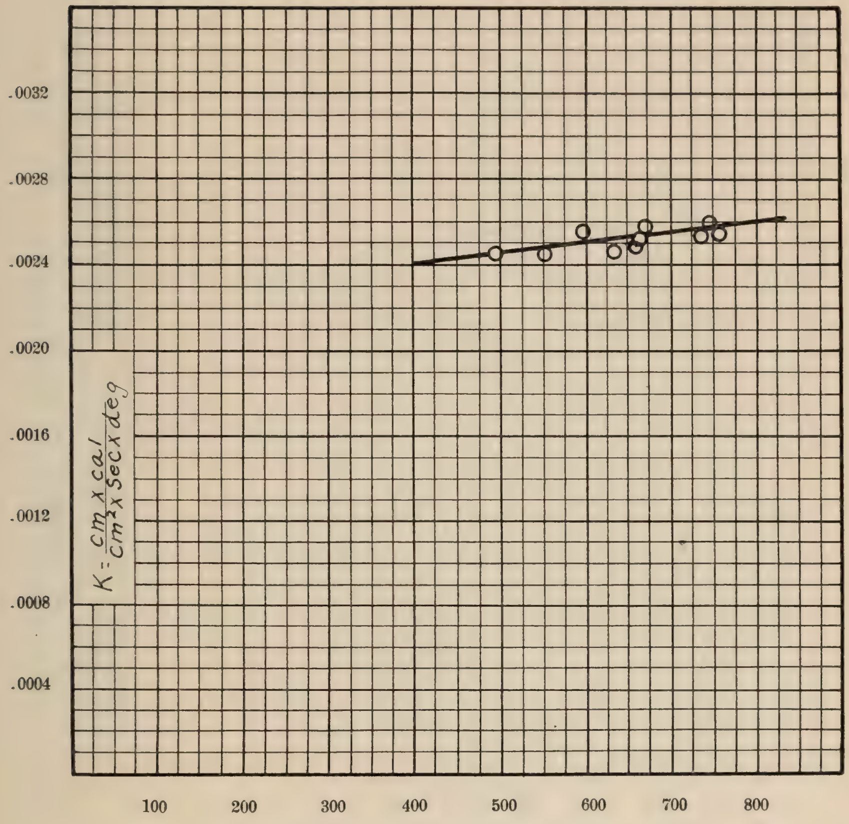
Fig. 7



TEMPERATURE IN CENTIGRADE DEGREES

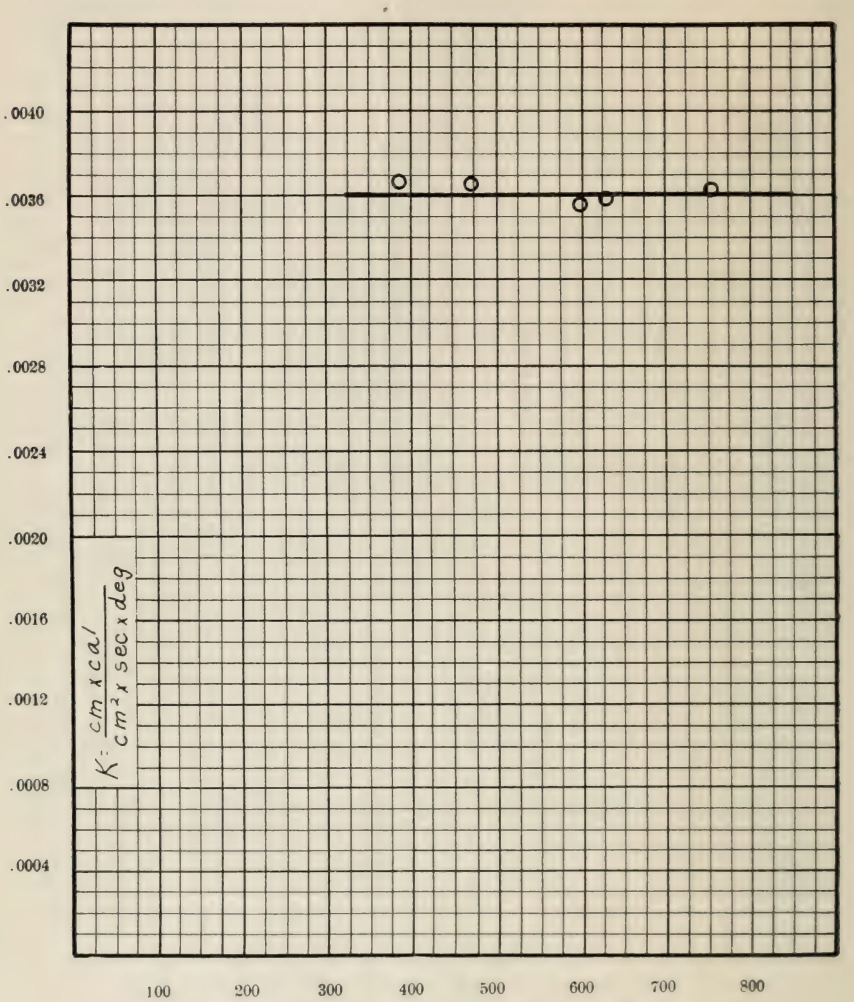
CURVE NO. 2

FIG. 8



CURVE NO. 3

FIG. 9



TEMPERATURE IN CENTIGRADE DEGREES

CURVE NO. 4

FIG. 10

APPENDIX

The use of thermocouples for measuring high temperatures is no longer a novelty in physical investigations, but the details of the calibration are not generally accessible. Hence the exact method of calibration used in this work has been described at considerable length in this Appendix.

METHOD FOR CALIBRATING THERMOCOUPLES FOR HIGH TEMPERATURE MEASUREMENTS

Since, as a rule, no two thermocouples have the same electromotive force, and since the electromotive force of any couple is appreciably changed by the action of metallic and possibly other vapors at high temperatures, it is necessary to calibrate the couples from time to time. The method described is that known as the *melting point* or *Frankenheim* method.[1] The couple, surrounded by a closed porcelain or fused silica tube, is immersed in the melted metal, and the furnace allowed to cool slowly. Readings of the electromotive force taken at regular intervals will show a steady decrease until the freezing point is reached, remain constant until the metal is nearly all solidified, and will then fall off again. Knowing the temperature at which the metal melts, we can thus determine the value of the electromotive force of the thermocouple corresponding to a definite temperature. Obtaining a number of points in this way by using different metals, a curve may be drawn through them showing the relation between the electromotive force and the temperature for that particular couple.

The Furnace.—Frequent use of this method demands a furnace which may be quickly and readily heated up and easily controlled. The furnace used in this work was a vertical furnace with an inside diameter of 2⅜ in. and a depth of 6 in. (see Fig. 11). The coil, which was of pure nickel wire about .072 in. in diameter, was first wound in one layer upon a collapsible wooden arbor. The wires were tied together by several longitudinal threads to keep them from springing out when the arbor was removed. A covering of paste, formed of water and a patent mixture, called "magnesite,"[2] was then applied. After the paste had dried, the coil was placed in a cylinder (also of a magnesite compound) 6¼ in. long and just large enough to contain it. The outside diameter was about 4½ in. The arbor was then removed, leaving the coil on the inside of the furnace, which had also been coated with the magnesite paste. This in turn was placed upon a fire-clay disc and surrounded by a cylinder of the same material,[1] the whole being covered with another fire-clay disc, usually in two pieces. The outside dimensions of the whole were about 8 in. in diameter and 9½ in. in height. The space between the magnesite cylinder and the surrounding one of fire-clay was filled loosely with calcined magnesia.[2]

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[1] (Holborn & Day). Amer. Jour. Science, Vol. 160, p. 171.

[2] Obtained from Harbison and Walker Refractories Company, Pittsburg.

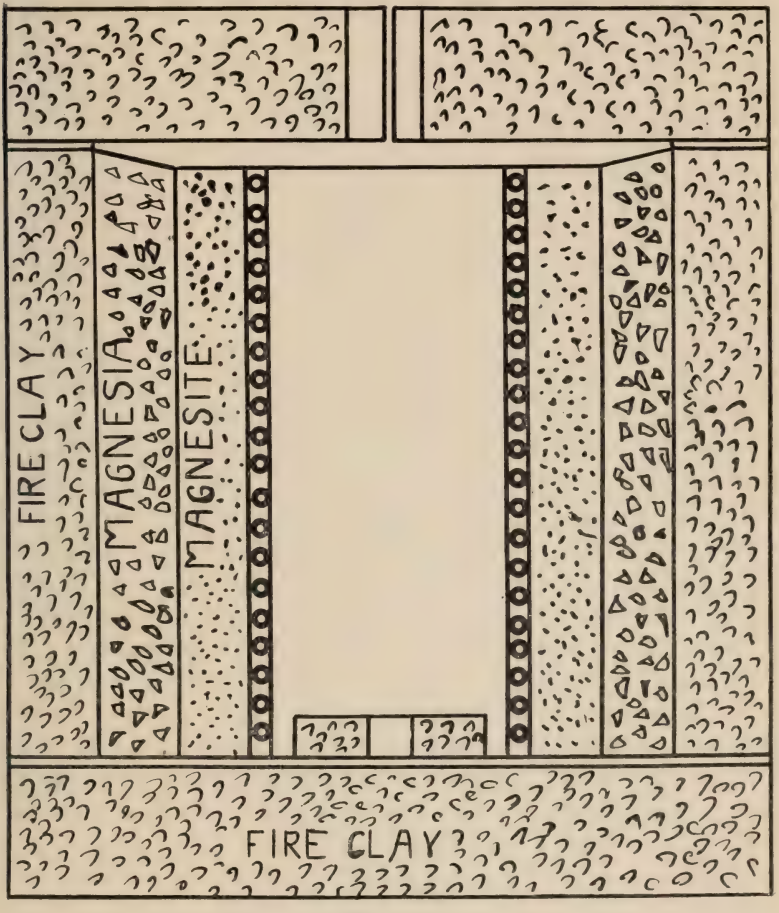

Fig. 11

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[1] Obtained from Dental Manufacturing Company, Buffalo, N. Y.

[2] Obtained from Eimer and Amend, New York City.

To avoid delay, in certain stages of the work, a furnace was used with a cylinder of magnesite instead of fire-clay. This was not so satisfactory, because more heat was lost through the magnesite than through the fire-clay; heavier currents were, therefore, required to maintain the necessary temperatures. With the furnace as described above, a temperature of 1000° C. could be obtained in less than two hours with a current of 25 amperes; and it could be maintained with 19 or 20 amperes.

Heating Circuit.—The arrangement of the heating circuit is shown in Fig. 12. The current was obtained from 110-volt continuous current mains and was regulated by two large Cutler-Hammer rheostats or "theatre dimmers." One of these had a current-carrying capacity of 125 to 50 amperes and a resistance of 4 ohms. The other was specially made and had a fixed resistance of 4 ohms, with 30 amperes carrying capacity, which could be short circuited, and also had a variable resistance of 6 ohms, with 30 to 10 amperes capacity. The low resistance rheostat permitted very small adjustments of current.

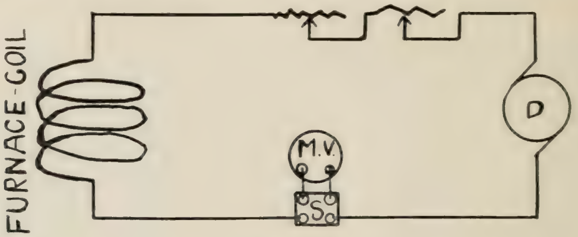

Fig. 12

Graphite Crucibles.—The charge of metal used was placed in graphite crucibles to a depth of at least 2 in. Fig. 13 shows the shape and size of these vessels. Such crucibles may be purchased from supply houses, but it is preferable to turn them out of graphite rods because the purity of the graphite rod is more certain.[1] The exact dimensions are not specified nor are they necessary so long as they will contain a charge of metal which is large compared with the silica tube surrounding the couple. It is important, however, that the inside of the crucible be tapered so that the charge may be removed. The covers are also of graphite and have a hole in the center for the insertion of the silica tube containing the thermocouple.

Thermocouples.—The thermocouples used in this work consisted

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[1] Acheson Graphite Co., Niagara Falls, N. Y.

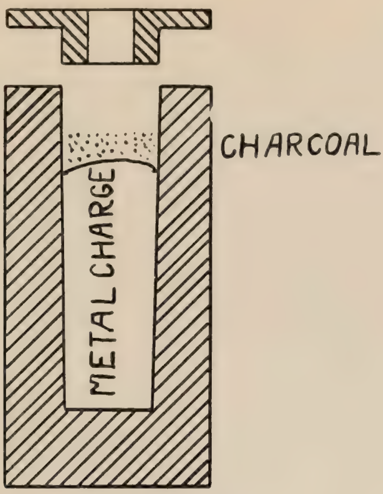

FIG. 13

of one wire of pure platinum and another of 90 per cent platinum and 10 per cent rhodium. The wires were each 0.6 mm. in diameter and 5 ft. long. The two wires were insulated from each other by pieces of very small porcelain tubing which were placed on the platinum-rhodium wire (see Fig. 14). The junction was then placed in a tube of fused silica, closed at the lower end. This tube, containing the wires and capillary porcelain tubing, was thrust into the melted metal to within about 5/8 in. from the bottom of the crucible.

The protecting tubes of fused silica[1] were about 1/4 in. in diameter and long enough to extend well out of the furnace. They were supported by a tripod and clamp at the upper end. A broken tube may be readily closed at one end in an electric arc or an oxy-hydrogen flame. Silica tubes as small as 2 mm. inside diameter may be used for this work by dispensing with the porcelain tubing on the platinum-rhodium wire, and separating the wires with strips of mica. This arrangement has considerable advantage, enabling one to get a much better curve; a smaller charge of metal can also be used. It is, however, not advisable to use the smaller tubes where a number of couples are to be calibrated, and where time is of importance, as it is difficult to insert the wires in the tube and keep them separated.

Cold Junctions.—The other ends of the wires were soldered to copper wires and kept at 0° C. The arrangement of these junctions

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[1] Eimer and Amend, New York City.

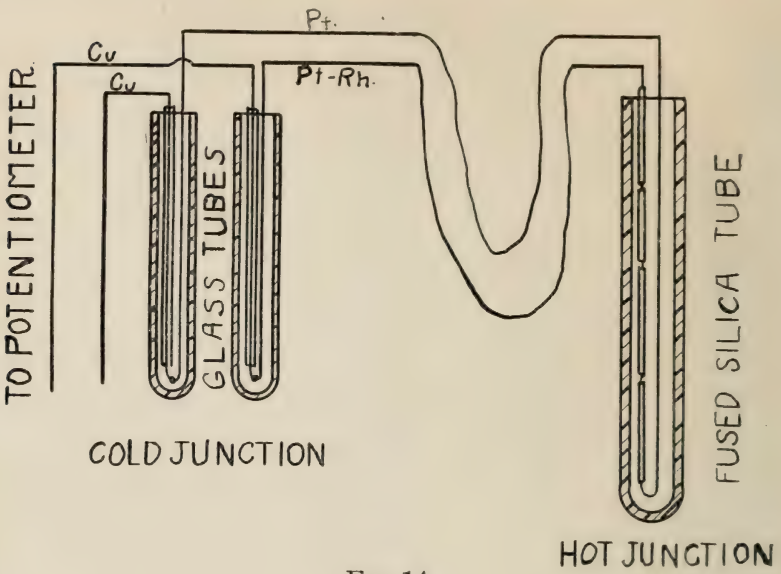

FIG. 14

(see Fig. 14), was similar to that of the hot junction except that glass tubing was used in the place of the quartz and porcelain. They were kept at the ice point by placing them through the lid of a double-walled bucket, which contained a mixture of ice and water. This bucket was packed with sawdust between the two walls.

Metals Used for Fixed Points.—The metals used for calibrating the couples were zinc in an oxidizing atmosphere, melting at 419° C.; silver in a reducing atmosphere, melting at 961.5° C.; and copper in a reducing atmosphere, melting at 1084° C. These values of their melting points are the ones found by Holborn and Day, 1900, and are at present accepted by the German Reichsanstalt. Later values found by Day and Clement are somewhat lower, being 418.5° ± .1; 958.3 ± .5; and 1081.0 ± .5 respectively.[1] The charges of silver and copper were covered with powdered charcoal which was of a very pure grade. This was done because the values given above for these two metals were obtained in a reducing atmosphere.

Other metals which may be used are cadmium, 322° C.; and gold 1063° C. The melting point of cadmium is somewhat low for a platinum-rhodium couple. Above 1100°, nickel melting at 1435°, iron melting at 1505°, and platinum melting at 1720°, may eventually

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[1] Amer. Jour. Science, Vol. XXVI, Nov., '08.

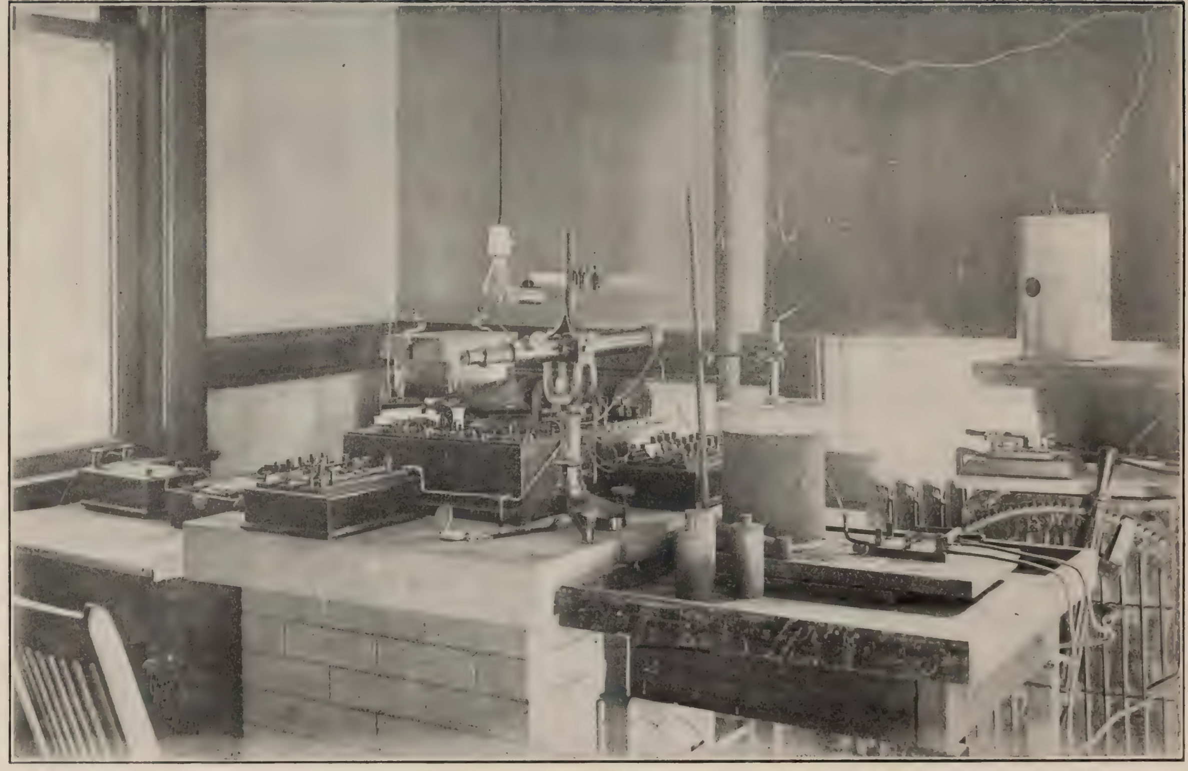

FIG. 15 SHOWING CALIBRATION FURNACE AND POTENTIOMETER

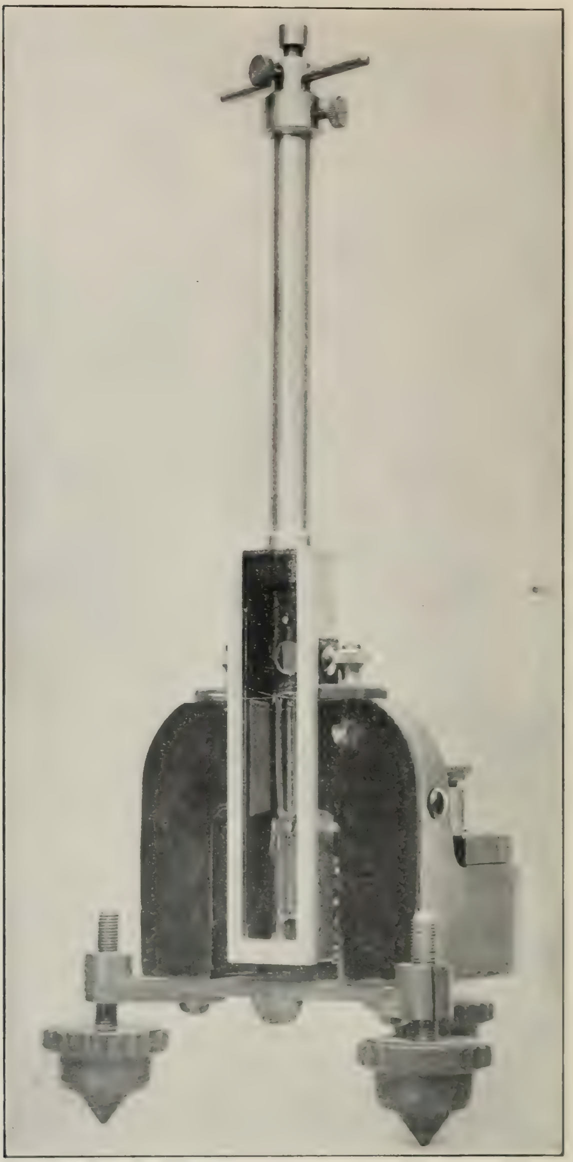

Fig. 16 Special Galvanometer Made for Use with Thermocouples

be available for fixed points, although it is not advisable to use any point above the copper point until the gas thermometer scale has been established above 1100°. A number of metals are unavailable for getting a fixed point on account of under-cooling.

It is of importance that the metals used for fixed points be of the highest purity, since any impurity alters the melting point.

Typical Set of Readings.—Below is given a typical set of readings taken with couple *F* (see p. 10), at the zinc melting point. The readings are in micro-volts or .000001 volt. The first column was taken with 8 amperes flowing through the furnace. After the zinc had solidified, the current was increased to 17.5 amperes, and as the zinc melted, the readings in column two were taken. The readings were taken regularly at intervals of 30 seconds.

8 Amperes		17.5 Amperes	
3461		3404	
3440		3412	
3431		3415	
3430		3418	
3429		3421	
3429		3423	
3429		3425	
3429	Freezing Point 419° C.	3426	
3429		3427	
3429		3428	
3429		3428	
3428		3429	Melting Point 419° C.
3428		3429	
3426		3435	
3420		3460	
3414		3490	
3400			

It may readily be seen from these curves that the transition points can be fixed better from the cooling curves than from the melting curves, because the bend of the curve is sharper and the flat part of the curve is better defined. Hence the cooling curve is the one used. It is much more definite and may be repeated, while the heating curve is often a little below the actual temperature, due to the lag in the charge and conduction of heat by the tubes.

Potentiometer and Galvanometer.—The electromotive force of the couples was measured with a Wolff potentiometer and galvanometer; a combination of the compensation and galvanometer methods being used (see Fig. 17). The Wolff box was connected in series with an adjustable resistance, R_1, of a little over 5000 ohms, and a single storage cell. As the resistance of the potentiometer was 15 000 ohms, the current could then be adjusted to exactly .0001 ampere. This was done by connecting a standard cell, (*Cd.*), of 1.0197 volts, across a resistance in the box of 10 197 ohms, and adjusting the series resistance, R_1, until the galvanometer, *G*, showed no deflection on closing the circuit. A reading of one ohm on the box then corresponded to .0001 volt or 100 micro-volts. As the smallest divisions of the box are 0.1 ohm, this gave a sensibility of 10 micro-volts, or about 1° C.

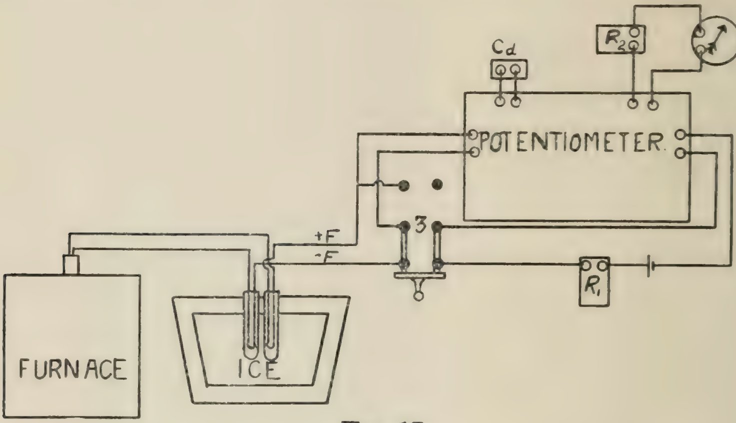

Fig. 17

The galvanometer [1] had a period of four seconds on open circuit and a sensibility of 2.85 micro-volts or 210 megohms. Its resistance was 230 ohms. It was used with a telescope and scale at a distance of about 150 centimeters.

A small resistance, R_2, was connected in series with the galvanometer, and this was adjusted so that the last dial on the Wolff box corresponded to a deflection of ten divisions of the scale. This increased the sensibility of the apparatus tenfold, as one scale division thus corresponded to 1 micro-volt or about 0.1° C. This adjustment was accomplished by first closing the battery circuit, setting the potentiometer on zero, and short-circuiting the thermocouple circuit. Such a value of R_2 could then be found that a movement of one division of the next to the last dial on the box, would give a deflection of exactly one hundred scale divisions. Of course as the setting of the box is increased or diminished, R_2 would have to be decreased or increased a corresponding amount, to keep the sensibility constant.

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[1] D'Arsonval type made especially for this work by Leeds & Northrup Co.

Scale and Telescope.—The scale used with the galvanometer had divisions about 0.6 mm. in length. One half of the scale was marked with red and was numbered from 800 at the end to 1000 or 0 at the center. The other half was black and was numbered from 0 at the center to 200 at the other end. The galvanometer was so connected that deflections toward the black figures indicated an addition to the potentiometer reading, and those toward the red figures a subtraction from it. The advantage of having the red scale read backwards, that is from 1000 to 800, is that negative deflections are already subtracted when read. For example, a negative deflection of 15 divisions would read 985. This, besides being a great convenience, also reduces to a minimum the chance of error in subtracting the galvanometer reading from that of the potentiometer.

Telescope.—The telescope used was a Hartmann and Braun instrument with horizontal and vertical tangent screw adjustments. These adjustments are a great convenience, the horizontal adjustment for setting the scale to zero being almost a necessity.

Manipulation.—When readings were to be taken at regular intervals as in the above set, the current was first adjusted, as described above, by comparison of the potentiometer with the standard cell. The galvanometer was then short-circuited through the Wolff box by the ''double-pole double-throw'' switch shown in Fig. 17. In the position shown, this switch closes the main potentiometer circuit with the storage cell, with the right hand blade, and connects the thermocouple to the potentiometer with the left hand blade. The pole on the left was shortened so that the right side made contact first, thus closing the main circuit before the galvanometer circuit was closed. By reversing this switch, the battery circuit is opened and the galvanometer circuit closed through the potentiometer only. The galvanometer scale was set at zero before each reading with this switch in the reverse position. This eliminates errors due to stray electromotive forces which may be in the circuit. The switch is then again changed, and the dials on the box adjusted until the galvanometer is as near zero as is convenient. Care is then taken to get the reading on the scale at the exact end of the interval, and adding (or subtracting) this reading to that indicated on the box. It is readily seen that when using the galvanometer reading in addition to that of the potentiometer, it is more convenient to have a box that may be adjusted by steps, rather than by a continuous contact along the winding.

External Influences.—Great care had to be taken with this arrangement of apparatus to avoid magnetic disturbance and electric leakage from the power circuit. Little trouble was experienced in cold dry weather with electric leakage, but during the warm moist weather of summer, it sometimes seemed almost impossible to avoid leakage.[1]

Formula for Calculating Temperature.—The formula which was used for calculating the temperature is $t = a + be + ce^2$, e representing micro-volts. Substituting the values for t and e obtained from the zinc, silver and copper points, we have three equations as follows:

$$t_1 = a + be_1 + ce_1^2$$

$$t_2 = a + be_2 + ce_2^2$$

$$t_3 = a + be_3 + ce_3^2$$

The values of e_1, e_2 and e_3 obtained for couple F used in the thermal conductivity work (see p. 10), were 3429, 9101 and 10534, respectively. Solving the above equations for a, b, and c, and substituting for t_1, t_2, t_3, e_1, e_2, and e_3,

$$a = 46.41$$

$$b = .11356$$

$$\text{and} \quad c = -1.4300 \times 10^{-6}$$

The temperatures measured by this couple are found by the equation

$$t = 46.41 + .11356\,e - .00000143\,e^2.$$

This parabolic equation is the one generally accepted at the present time for the platinum alloy couples when the cold junction is at 0°, although it will not hold below 250° C., and can be used only approximately below 350° C. If the cold junction is above the ice point, a correction must be added to the observed temperature, equal to 0.5 times the temperature of the cold junction in Centigrade degrees.

$t = t$ (obs) $+ 0.5 \times$ *temperature of cold junction.* The possible accuracy of the above equation is about 0.5° C., between 350° and 1100° C. The probable accuracy of the temperatures as measured above is about 1° over the same range, though the sensibility is 0.1° C.

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[1] Discussion by W. P. White, Physical Review, 1907.

Other equations have been offered by Regnault, Avenarius and Tait, Stansfield, and others, but are not used at the present time. References [1] on thermal electricity are given below.

Galvanometer Method.—For work which does not require such a high degree of accuracy, it is more convenient to use a galvanometer alone for reading the electromotive force. With a galvanometer of about 400 ohms resistance, by taking proper precautions, the readings are reliable within 5° C. up to 1100° C.

Lower Temperatures.—For temperatures below 400°, a copper-constantan couple will be more satisfactory, as it has about four times the thermo-electric power of the platinum-rhodium couple. It may be used from 0° to 500°.

Contamination.—Great care must be taken to avoid contamination of the platinum couples, as they are very readily attacked by metal vapors at the higher temperatures. The readings of the couple will be lowered by contamination. The couple can be restored only by removing the contaminated portion. With care, however, contamination may be avoided and the readings of the couple kept constant. The two couples used in the conductivity work described on p. 10 did not change within the sensibility of the measurements during four months of almost continuous use.

---

[1] A Text-Book of Physics (Watson), p. 714.

High Temperature Measurements (Le Chatelier), p. 120.

A. Stansfield on Some Improvements in the Roberts-Austin Recording Pyrometer, Phil. Mag. July, 1898, p. 73.

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